THE UNIVERSITY OF QUEENSLAND

Bachelor of Engineering Thesis

Experimental Investigation of the Effect of Water and Temperature on Mechanical Properties of Rocks

Student Name: Chun Ling Patrick Lau

Course Code: MINE4123

Supervisor: Dr Zhongwei CHEN and Mr Morteza Ghamgosar

Submission date: 6 November 2016

A thesis submitted in partial fulfilment of the requirements of the Bachelor of Engineering degree in Mining Engineering

UQ Engineering

Faculty of Engineering, Architecture and Information Technology

STATEMENT OF ORIGINALITY

I, Chun Ling Patrick Lau, hereby declare that this research project proposal is my own work and that it contains, to the best of my knowledge and belief, no material previously published or written work by another person nor material which to a substantial extent has been submitted for another course, except where due acknowledgement is made in the report.

Chun Ling Patrick Lau

ACKNOWLEDGEMENTS

I would like take this opportunity to express my sincere gratitude to my supervisors Dr. Zhongwei Chen and Mr Morteza Ghamgosar. Thank you for accepting me as part of your team and it is my honour to be one of your students. Since the beginning of this project, I have been constantly receiving your guidance for conducting experiments and data analysis. Thank you for being so patient throughout the year, as you would promptly answer my enquiries and provide constructive feedback on my work. Under your supervision, I have broadened my mind and deepened my knowledge in rock mechanics. Also, I would like to thanks Golder Associate of providing samples for me to do the research.

I would also like to give thanks to my family who showed great patience and endless care along the way even we are living in two different countries. I would like to thank you all once again for directing me throughout the project and sparing your precious time to help me. This project would not be able to complete successfully without all of your assistance.

ABSTRACT

In mining or civil operation, geological challenge could be encountered when excessive groundwater is present in the field. Artificial ground freezing is one of the effective methods to control or mitigate the potential of groundwater inflow. However, uncertainties still remain in terms of understanding and predicting the behaviour of rocks under sub-zero temperature. The main aim of the research is to investigate effect of temperature and water on the mechanical properties of rock by conducting the cracked chevron notch Brazilian disc (CCNBD) standard fracture toughness test. The dimension of the samples (Sandstone and Basalt) was prepared based on ISRM suggested guidelines. The CCNBD test was conducted in four different temperatures (25^0C, -25^0C,-50^0C, and -75^0C) under dry and wet condition. The obtained fracture toughness values from the test were correlated with temperatures, so that the change in fracture toughness in each temperature could be observed.

The experimental results determined for sandstone showed that the fracture toughness in both dry and wet conditions increases as temperature decreases. In addition, fracture toughness was found to be lower for wet samples at 25^0C relative to dry samples and such value was 0.44 $\mathbf{MPa\sqrt{m}}$ and 0.55 $\mathbf{MPa\sqrt{m}}$ respectively. The reduction in fracture toughness at 25^0C is possibly due to the weakening effect of water which causes the microcracks within the specimen to enlarge and extent and therefore resulting in a reduction of strength. However, when temperature drops below 0^0C, the strength of rocks become a combination of ice strength and rock strength. Hence the strength of ice as well as the strength of rock increases as temperature continuously decreases. Furthermore, another observation can be seen from the result of sandstone is that the temperature has a greater effect on wet samples as the increasing rate of fracture toughness is much faster than dry samples. Such increase rate for wet samples can fit into a logarithmic relation but it is only a linear relation for dry samples. In addition, the differences in strength between wet and dry sample can be up to 120% when temperature is at -75^0C. One of the main reasons is that since the ice content of wet samples is larger than in dry samples, the strength of ice enhances the rock strength significantly as temperature decreases. In addition, the result of basalt in dry condition showed similar results. The fracture toughness can increase up to 14% when temperature reaches -75^0C. When temperature decreases, the mineral grains within the rock specimen shrunk which generated a confining stress to the specimen and result in a higher compressive strength. To conclude, temperature has a positive impact on the strength of rocks and wet samples are more sensitive to the change in temperature.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

1. INTRODUCTION

1.1. BACKGROUND

In mining or civil application, geotechnical challenge could be encountered if excessive ground water is present in the field. Artificial ground freezing is one of the most effective ways to control the potential of ground water inflow. It requires the use of refrigeration pipes by pumping liquid nitrogen or brine to the ground and turns in-situ pore water into ice. Such application has been used as an excavation support in shaft sinking. However, uncertainties still remain in terms of understanding and predicting the behaviour of rocks under sub-zero temperature. As previous researches were mainly focusing on the behaviour of frozen soil and the majority of the studies that are related to the behaviour of rocks were conducted under room temperature condition. The knowledge of the mechanical properties of rock under sub-zero temperature is important not only in terms of efficient rock excavation but also in terms of safety perspective as well, as it could be used to assess the stability condition of tunnels or rock caverns in cold regions. It is therefore important to develop a better understanding on the behaviour of rock properties under sub-zero temperature.

1.2. AIMS AND OBJECTIVES

The main aim of the research is to investigate effect of temperature and water to the mechanical properties of rock by conducting cacked chevron notch Brazilian disc (CCNBD) standard fracture toughness test. Fracture toughness is a key parameter in rock fracture mechanics as it is a fundamental property of rocks which uses to describe the ability of resistance to crack propagation. The data obtain from the test could help to develop a series of laboratory database for each tested sample which could help similar case study in the future. The test was conducted according to the standardised methods proposed by International Rock Mechanics Society (ISRM) as this could provide more consistent value from the test. In order to achieve the aim of the research, several objectives are required to be met:

- Conducting standard fracture toughness test to soft and hard rock – Basalt and Sandstone

- Provide an experimental correlation between fracture toughness values and temperature
- Compare the effect of temperature to sandstone and basalt

1.3. SCOPE

The project was to examine the degree of impact of temperature and water on rocks. Activities that lied within and out of the scope are summarized in Table 1. Since the aim of the project was focusing on the behaviour of rock under low temperature, the behaviour of rock in high temperature is out of scope.

Table 1
Scope of the Project

In Scope	**Out of Scope**
Conduct fracture toughness test using CCNBD method	Conduct fracture toughness test using other methods (e.g short rod, and chevron bend)
Loading the CCNBD sample in zero inclination	Loading the CCNBD sample in various inclination of the chevron crack alignment
The rock samples will be tested at room temperature and various sub-zero temperature	Loading sample with dynamic and cyclic loads
The fracture toughness test is carried out to study rock sample in dry and wet condition	Study the fracture distribution of rock greater than room temperature
Fracture toughness will be calculated to correlate with temperature for each sample	Microfracture analysis by using X-ray tomography
Comparing the result between sandstone and basalt	Numerical modelling based on the calibrated results obtained from standard experimental test

1.4. SIGNIFICANCE TO THE INDUSTRY

A complete understanding of fracture toughness is important as imminent rock mass failure can be predicted and identified. A variety range of applications such as rock cutting, blasting, and tunnelling can be benefit by studying fracture toughness as it has correlation with rock fragmentation process. In terms of rock cutting performance, cutters can be improved as the cutting force can be represented as a function of fracture toughness and cutting depth (Deliac, 1986) and also rock fracturing machinery can be optimised as well because it is a key parameter of material property in rock fragmentation modelling (Whittaker, Singh and Sun, 1992). In terms of blasting it can be used to optimise a blast design as it has strong relationship with the specific comminution energy therefore it can used to predict the comminution energy that is required to reduce a rock particle to a given size based on fracture toughness value (Donovan, 2003). Moreover fracture toughness can also be beneficial to tunnelling as well. As it can be used to estimate the penetration rate of a tunnel boring machine so that performance of TBM can be predicted (Guo, Aziz and Schmidt, 1993). In addition, Clark (1987) showed that fracture toughness is an ideal measure to predict the performance of TBM as it has less variability relative to other material properties such as uniaxial strength, tensile strength, and point load strength. Apart from practical application another advantage of this research can provide a series of laboratory database for particular rock types and also it can be used in the similar case study in the future as well.

2. LITERATURE REVIEW

2.1. FRACTURE MECHANICS

2.1.1. Fracture Initiation & Propagation

Brittle materials such as rocks have different kinds of flaws and micro-fractures that are inherent within the rock matrix. It also contains minerals with different grain sized and cracks which contributed to the effect on fracture process when it is under static or dynamic loading (Ghamgosar and Erarslan, 2014). The strength of different types of rocks is unique as they compose of different types of minerals. When the rock under stresses that reaches the critical level, initial cracks will form and interact with its discontinuities which result in the development of micro-cracks to unstable zone and ultimate failure due to the coalescence of cracks (Ghamgosar & Erarslan, 2014). The general process of rock failure can be expressed in a stress strain curve as shown in Figure 1. When compressive stress is applied to the rock, crack that inherent within rock will close due to the compression. The stress-strain curve is in a non-linear relationship during the process of crack closure which exhibits an increase of axial stiffness (Eberhardt et al., 1998). In addition, the extent of the non-linear region depends on two factors - initial crack density of the rock and geometrical characteristics of the crack population (Eberhardt et al, 1998). When most of the pre-existing cracks have closed, the rock deform linear elastically which is the elastic constant, Young's modulus, of the rock. Within this region, the deformation can reverse back to its original state. However, if load keep on the increase and reaches the critical level microfracturing will start. At that point, both lateral and volumetric strain curves start to deviate from the linearity. The microfracturing process will occur once the load passed the linear elastic deformation zone and it will propagate under a stable condition (Bieniawski, 1967). In the process of stable fracture propagation, elastic energy will be released to extend the crack surface. Once critical energy is attained the unstable fracture propagation begins. The definition of unstable crack propagation is 'the condition that occurs when the relationship between the applied stress and the crack length ceases to exist and other parameters, such as the crack growth velocity, take control of the propagation process' (Bieniawski, 1967). In such condition the growth of cracks would continue even if the applied load were kept constant (Eberhardt et al, 1998). The unstable crack growth will continue until it reaches the maximum strength of the rock where numerous of microcracks have coalesced and the rock itself cannot withstand any more load (Eberhardt et al, 1998). If further load is applied the rock will rupture and complete disintegrate.

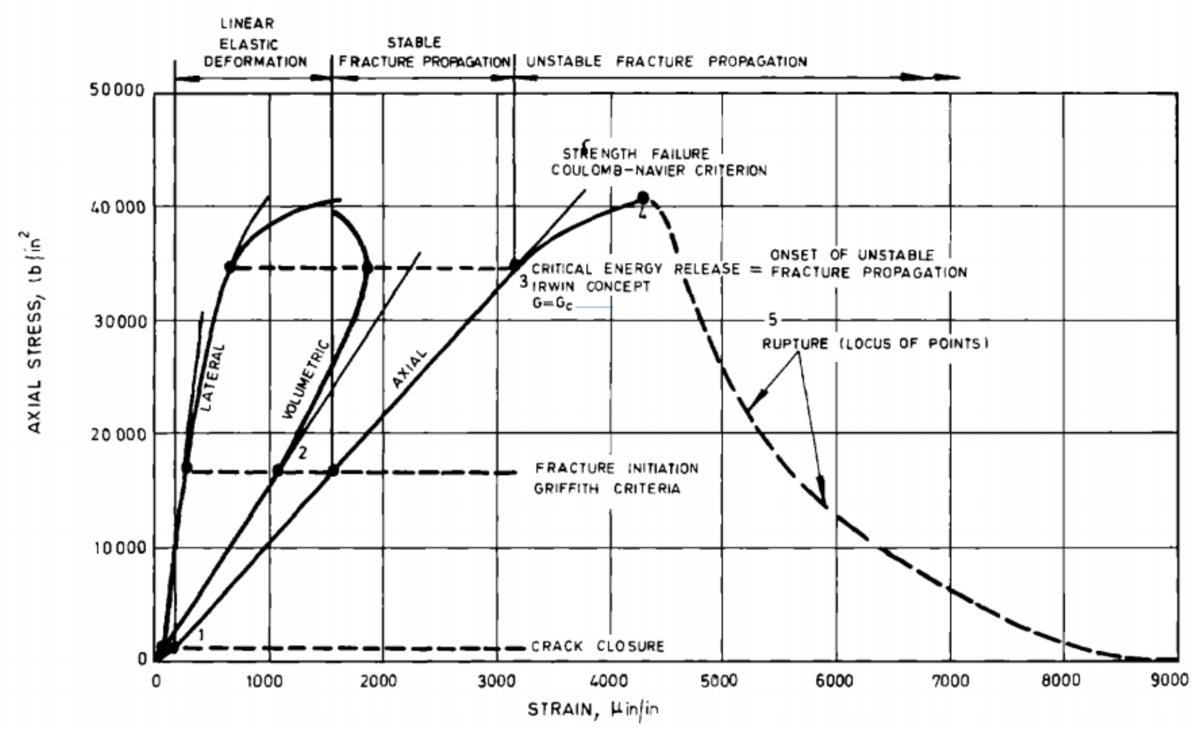

Figure 1. Stress vs Strain (Bieniawski, 1967)

2.1.2. Development of Fracture Process Zone

There are a lot of experiments have been done which proved that when the rock is under compressive loading both shear and tensile stress will develop and concentrate in the pre-existing inhomogeneity at meso and macro sale (Hoek and Bieniawski (1984); Tang et al. (2001); Sagong and Bobet (2002)). When the applied compressive load further increase, tensile cracks will begin to from at the tip of pre-existing flaws which has already been discuss in the previous section. These tensile cracks called wing cracks will propagate in the direction of the major principle stress (Backers, 2004). When load increases secondary cracks will form and initiate at the tip of flaws. The direction of secondary cracks propagation can be coplanar or quasi-coplanar to the flaw and can also be parallel to the wing crack but in opposite direction as shown in Figure 2 (Bobet, 2000). Secondary cracks play an important role in fracture process when rocks are under compressional stress as fracture coalescence caused majorly by secondary cracks (Bobet, 2000). The coalescence of fracture behaviour depends on the geometry of interacting fracture as well as the stress condition. Fracture process zone (FPZ) which illustrated in Figure 3 is an area contains various types of damage involved around the pre-existing or stress-induced crack tips within the rock (Ghamgosar & Erarslan, 2015). The damaged area consists of micro and meso-cracks which occur prior to main fracture extension and they will eventually coalescence to become macrofracture which results in failing.

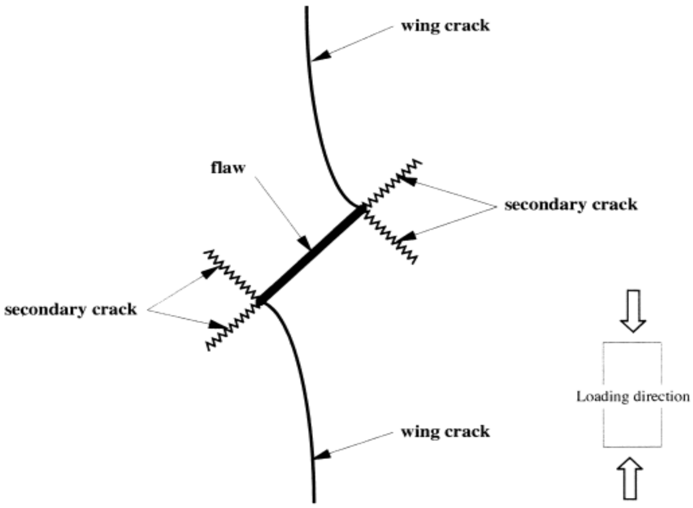

Figure 2. Crack Pattern Observed in Pre-cracked Specimens of Rock Material in Uniaxial Compression (Bobet, 2000)

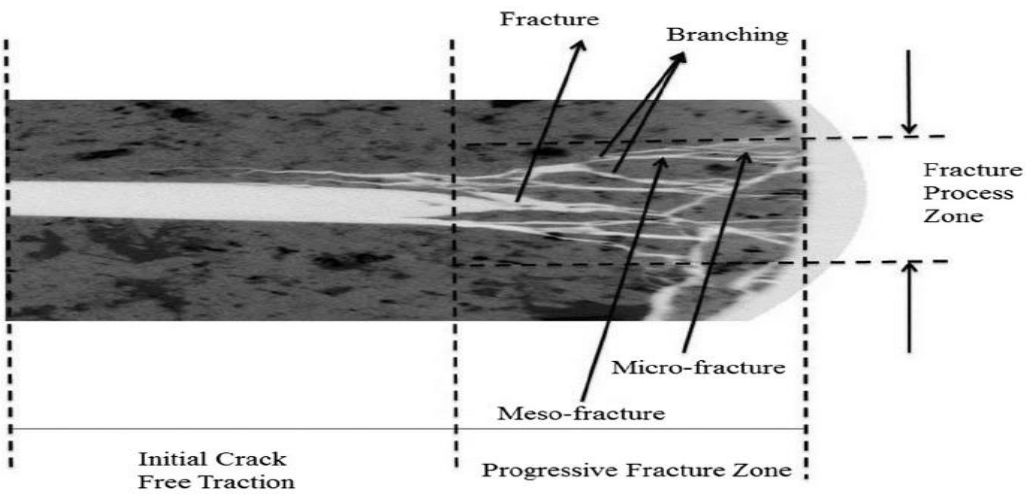

Figure 3. Fracture Process Zone (Ghamgosar & Erarslan, 2015)

2.2. Effect of Water on Rock Properties

2.2.1. Sedimentary Rocks

The effect of water on sedimentary rocks has been studied widely in the past. Many of researchers found that the compressive strength of saturated sedimentary rocks such as sandstone is much lesser than the dry sample. Van Eeckhout (1976) investigated the effect of water on the strength of different kinds of sedimentary rocks. He observed the strength of fine grain sedimentary rock has significantly reduced when water content increase from dry to saturated condition. He suggested the reduction of strength due to increase of moisture is caused by five different processes (Van Eeckhout, 1976): chemical deterioration, reduces in fracture surface energy, decrease in capillary tension, increase of pore pressure, and reduce in fraction.

Price (1960) found that the reduction of strength as well as Young’s modulus of sandstone is highly depends on the amount of clay content. In addition, the Young’s modulus would drop by 6-19% when the sample was saturated. However, another observation was obtained by Collback and Wiid (1965). They found the uniaxial compressive strength (UCS) reduced linearly by testing saturated quarzitic sandstone. Therefore the degree of strength reduction is mainly depends on the mineralogy of the rocks, as minerology will have impact on the microstructural feature (e.g. geometry of grain boundaries, grain-matrix relation, the presence of clayey matrix etc.) which dictate the absorption capacity of the rocks. Based on numbers of researches a common result was observed. The sensitivity of weak sedimentary rocks to moisture content is more than strong sedimentary rocks as they have higher absorption capacity (Hawkin and McConnell, 1992). When water is present in a sedimentary rock such as sandstone, the mechanisms of weakening are through three steps. Firstly water penetrates rock through the pre-existing micro discontinuities. Secondly water will cause the clay mineral to swell and weaken the silica-oxygen bonding within sandstone by converting it to a much weaker hydrogen bond (Dyke and Dobereiner, 1991). Thirdly such effect result in the connection and propagation of cracks (Jiang et al, 2014). Furthermore, other than water weakening effect the strength and modulus can also reduce by alternating wetting and drying effect as this result in structural changes in rock which weaken the intergranular bonding and hence reduce in modulus value (Burshtein, 1969).

A numerical relationship between the effects of water content on the mechanical properties of sandstone has been investigated by Vasarhelyi (2003). He summarized the data and showed the relationship between dry UCS and fully saturated UCS has a linear relationship which can be expressed in the Equation 1 as shown:

$$\sigma_{csat} = 0.759\sigma_{c0} \tag{1}$$

where

σ_{csat}: saturated UCS

σ_{c0} : dry UCS

Also, the correlation between the compressive strength and water content can be expressed by Equation 2 as well

$$\sigma_c(w) = ae^{-bw} + c \tag{2}$$

where

$\sigma_c(w)$: UCS

w : water content

a,b, c : constant

In addition, porosity and the amount of clay mineral are the factors that influence the tensile strength of sandstone. Ojo and Brook (1990) proposed water can reduce the tensile strength of sandstone up to 50%.

2.2.2. Igneous Rock

The effect of water to the mechanical properties on ingenious rocks is found to be different with sedimentary rocks. Kessler, Insley and Sligh (1940) tested the compressive strength of 161 different types of American granitic rocks under wet condition and the results showed that the strength reduce by 12% relative to dry samples. Furthermore, Ruiz (1966) did a similar test to various types of igneous rock including granite, basalt, and gneiss under saturated condition and the reduction in strength are similar result as well. Based on such findings it can be seen that the effect of water to the strength igneous rock is much lesser than sedimentary rock. However, the reduction in UCS of both tuffs and diabase was found to be more severe relative to others rocks due to water weakening effect. The reduction of UCS for tuff was 2%-88% and diabase was 40% (Ergular and Ulusay, 2009).

2.3. EFFECT OF SUB-ZERO TEMPERATURE ON PROPERTIES OF ROCK

Temperature was found to have direct impact to the compressive and tensile strength of rock. Mellor (1973) tested various types of rocks including granite, limestone, and sandstone in temperature ranging from 25 ^{0}C to -195^{0}C under dry and saturated condition and the results are illustrated in Figure 4. Figure 4 shows that the compressive strength increase as temperature decreases by a factor of 1.8 for granite (crystalline rock) and a factor of 4 for sandstone and limestone (porous rock). When temperature decreases the mineral grins within the rock shrinks. The shrinkage of the mineral grains creates a confining stress condition in the rock and result in increases in compressive strength. Besides, the strength of ice is also a contributing factor of compressive strength as well. The pore water will turn to ice once temperature reach below 0^{0}C (Dwivedi, Soni and Geo, 2000). The strength of ice will increases as temperature decreases and hence the compressive strength of rock increases. Further research was conducted to investigate the effect of Young's modulus under low temperature by Yamabe and Neaupane (2001). Not surprisingly they observed that young's modulus increases as temperature decreases. However the increases of Young's modulus start to level off once temperature reaching -10^{0}C to -20^{0}C.

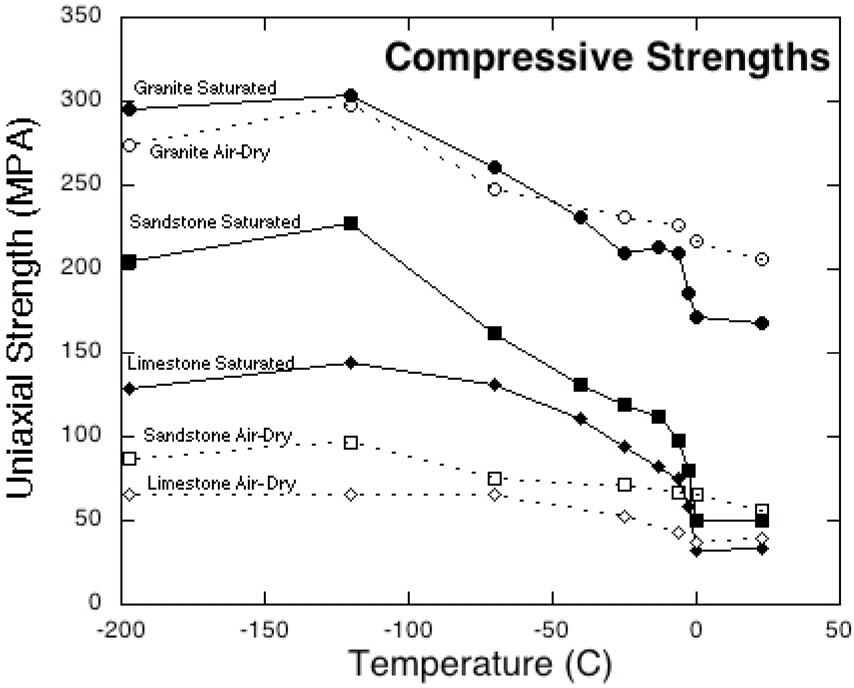

Figure 4.Uniaxial Compressive Strength vs. Temperature (Mellor, 1973)

3. EXPERIMENTAL APPROACH

3.1. FRACTURE TOUGHNESS TEST

Fracture toughness (K_{IC}) is a intrinsic material property that indicates the capacity of taking load or the resistance of fracture initiation or propagration of cracks. More specifically it is a critical value of stress intensity factor which quantify the severity of crack condtion witthin the rock (Dowling, 1999). Fracture toughness of a rock using core-based specimen can be determined by three different methods recommend by the Internation Society for Rock Mechanics (ISRM) – Chevron Bend (CB), Short Rod(SR), and Chevron Cracked Notch Brazilian Disc (CCNBD) methods (Fowell, 1995). In this particular study, CCNBD method will be used instead of the others two method. The reason for choosing CCNBD specimen because the preparation is more simple compare to the short rod specimen test and more importantly the result obtained is more applicable to practical purposes. Also, precrack for CCNBD specimen are not necessary as chervron notch is used (Ghamgosr & Erarslan, 2015). The CCNBD specimen will be loaded by the hydraulic compression machine in a biaxial direction with notch crack inclination angle of zero until it fails in mode I failure. The loading position should be placed as shown in Figure 6 where the upper and lower loading platform are required to be rigid and parallel to each other in order to generate a concentrated vertical load to the specimen. The magnitude of the force applied, diametral displacement and crack mouth displacement will be recorded continuously by a computerised data logger during the test. Such data was then later be used to calculate the dimensionless stress intensity factor and fracture toughness value. In addition, the fracture toughness value and dimensionless stress intensity factor are determined by Equation 3 and 4 (Fowell, 1995) as shown respectively:

$$K_{IC} = \frac{P_{max}}{B\sqrt{R}} Y_{min} \tag{3}$$

where

K_{IC} : Mode I fracture toughness

P_{max} : maximum load

B : specimen width

R : radius of the specimen

Y_{min}: criticial dimensionless stress intensity factor

$$Y_{min} = \mu e^{v\alpha_1} \tag{4}$$

where

Y_{min} : criticial dimensionless stress intensity factor

μ : a constant which can be determined from a table as shown in Appendix C

v : a constant which can be determined from a table as shown in Appendix C

α_1 : dimentionless notched crack length

3.2. SAMPLE PREPARATION

Two different types of rocks (basalt and sandstone) were used in the fracture toughness test and there are in toal 23 samples. In addtion, the sample ID of sandstone was named as S/CCNBD and basalt was named as B/CCNBD. Out of 23 samples, 15 samples were sandstone and 8 were basalt. The CCNBD specimen will be prepared by a fully digitize cutting machine mounted with a 40mm circular diamond saw which used to cut the notch that appears in the CCNBD samples and it will be cut from both sides of the disc as shown in Figure 5. The chevron V shape notch will provide a medium for stable crack propagation until it proceed to the unstable state and ultimately fail in tension (Ghamgosar & Erarslan, 2014). The standard CCNBD specimen geometry is illustrated in Figure 6 and the prepared samples are illustrared in Appendix A. In addtion, the dimensions of the CCNBD samples are prepared based on the ISRM standard and such values are summarised in Table 2 ,3, and 4.

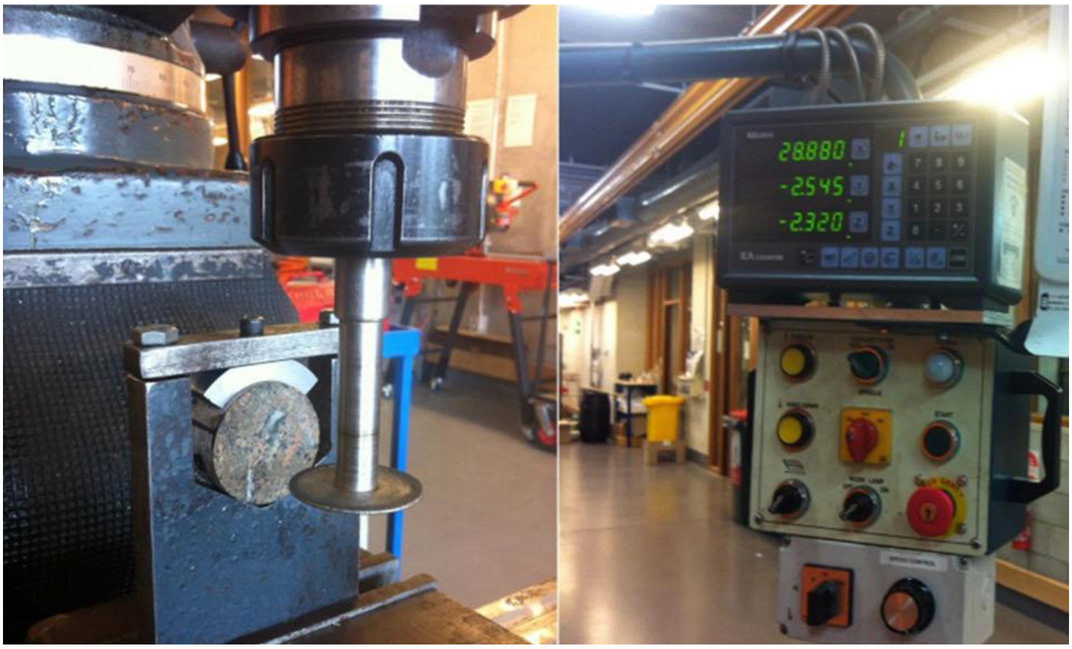

Figure 5 CCNBD Sample Preparation (Ghamgosar and Erarslan, 2015)

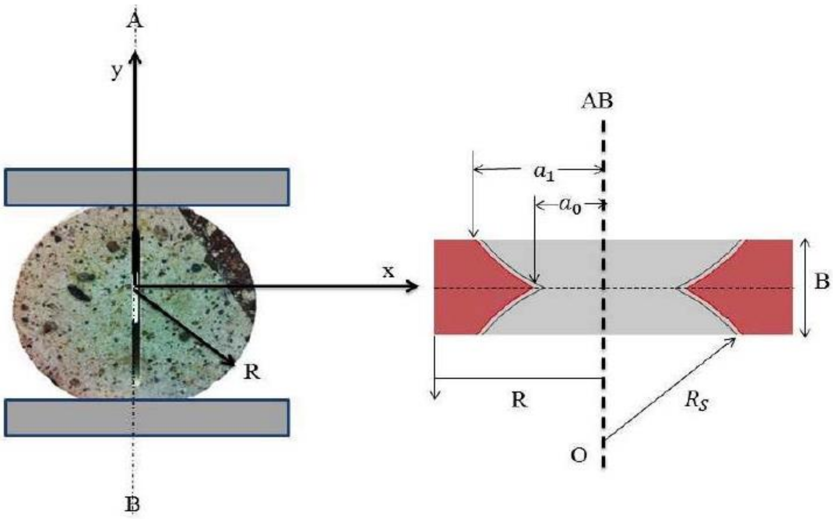

Figure 6. Geometry of CCNBD specimen (Ghamgosar and Erarslan, 2015)

Table 2
Dimension of CCNBD Sample (Dry Sandstone)

Sample ID	Temperature (ºC)	Radius R (mm)	Thickness B (mm)
S/CCNBD43	25	26.2	26.3
S/CCNBD1	25	26.1	26.9
S/CCNBD8	-25	26.2	26.7
S/CCNBD10	-25	26.2	26.8
S/CCNBD7	-50	26.1	26.7
S/CCNBD9	-50	26.1	26.8
S/CCNBD13	-75	26.1	26.7
S/CCNBD11	-75	26.1	26.7

Table 3
Dimension of CCNBD Sample (Wet Sandstone)

Sample ID	Temperature (ºC)	Radius R (mm)	Thickness B (mm)
S/CCNBD14	25	26.1	27.0
S/CCNBD2	25	26.1	26.8
S/CCNBD4	-25	26.1	26.8
S/CCNBD3	-25	26.1	26.9
S/CCNBD12	-50	26.1	26.7
S/CCNBD5	-75	26.1	26.7
S/CCNBD6	-75	26.1	26.6

Table 4
Dimension of CCNBD Sample (Dry Basalt)

Sample ID	Temperature (ºC)	Radius R (mm)	Thickness B (mm)
B/CCNBD2	25	26.1	26.7
B/CCNBD1	25	26.1	26.7
B/CCNBD4	-25	26.0	27.7
B/CCNBD3	-25	26.1	26.7
B/CCNBD7	-50	26.1	27.5
B/CCNBD6	-50	26.2	27.3
B/CCNBD8	-75	26.1	27.3
B/CCNBD5	-75	26.1	27.3

There are two dimension, the notched crack length α_1 and the ratio between the thinknees to diameter of the sample α_B, that need to be considered in order to obtain valid results. Such parameters have to fall within the valid geometrical region propsed by ISRM standard (Fowell, 1995) as shown in Figure 7. The finial chevron notched crack length (a_1) will be measured to determine the dimensionless parameter α_1 so that the result can be checked wether it was falling within the valid geometrical region. In addtion, the range of the boundary lines as shown in Figure 7 are summarized in Table 5.

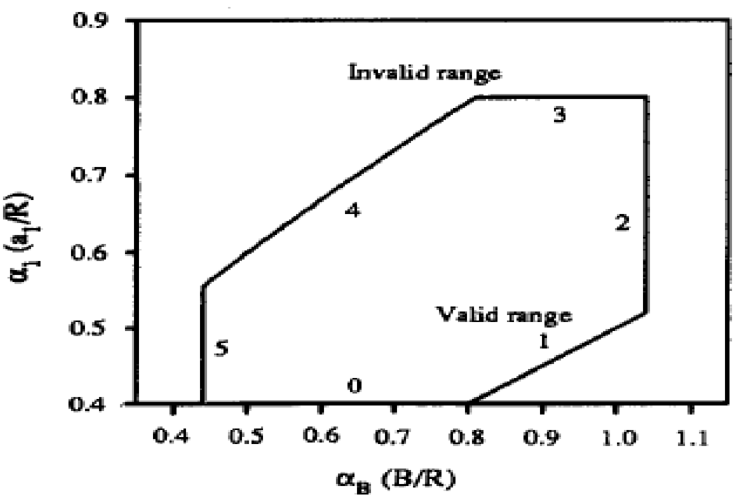

Figure 7. Valid Geometrical Range

Table 5
Restriction of Dimensionless Parameters

Boundary Line	Limit Range
0	$\alpha_1 \geq 0.4$
1	$\alpha_1 \geq \alpha_B /2$
2	$\alpha_B \leq 1.04$
3	$\alpha_B \leq 0.8$
4	$\alpha_B \geq 1.1729$
5	$\alpha_B \geq 0.44$

Source: Fowell (1995)

3.3. EXPERIMENTAL APPARATUS AND PROCEDURES

The apparatus required to perform the fracture toughness test are – hydraulic compression machine, environmental chamber, and cryogenic gas container. The hydraulic compression machine (Instron) is designed to apply load to the test sample by the moving cross head as shown in Figure 8. It has four major components – load frame, controller, load cell, and a computer system. Compression load can be exerted onto the test sample when the crosshead moving upward. A load cell and strain transducer is installed in the machine which can measure the magnitude of load applied and the strain during the test. The system is connected to a computer and control by Instron proprietary software program. The environmental chamber is designed to provide a cold environment for the sample to cool down the rock. Cryogenic gas (Liquid Nitrogen) will be blow into the chamber through the cooling valve which is connected to a self-pressurizing container that store liquid nitrogen as shown in Figure 8.

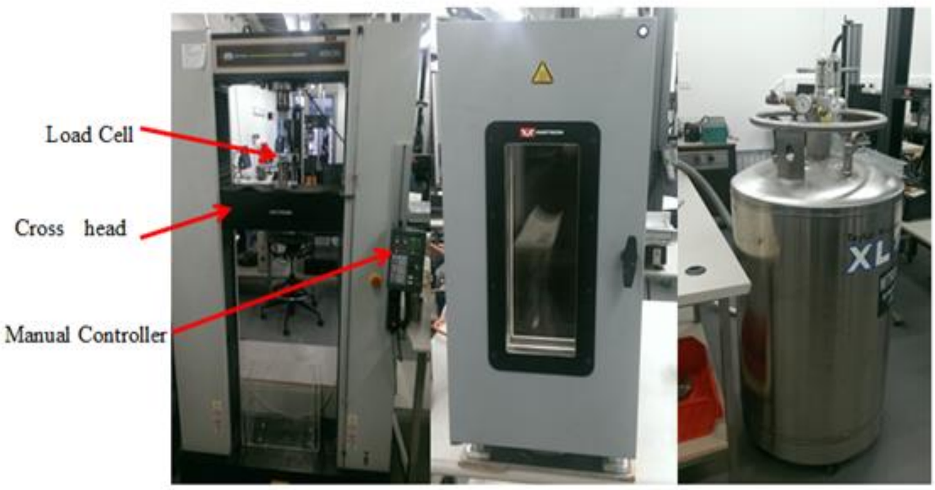

Figure 8. Experimental Apparatus (Left: Instron, Middle: Environmental Chamber, Right: Cryogenic Gas Container

To investigate the effect of temperature and water to the mechanical properties of both sedimentary (sandstone) and igneous rocks (basalt), the test was conducted in four different temperatures – 25^{o}C, -25^{o}C, -50^{o}C and -75^{o}C. 4 samples of sandstone (2 dry and 2 wet) and 2 samples of basalt (2 dry) would be tested in each temperature. In addition, only sandstone would be able to test under wet condition due to the availability of the samples. Samples that were tested in wet condition were placed in water bath for more than 1 week to ensure it was in saturated condition. Samples that need to be tested in the temperature below 0 ^oC will be cool down in the enviormental chamber by liquid nitrogen. To ensure the entire sample is at that specific temperature (e.g. -25 ^oC or -50 ^oC or -75 ^oC) samples were required to place in the environmental chamber for at least 30 minutes so that the core of the sample is at temperature as well.

When conducting the experiment, the prepared sample needs to be placed in middle of the loading platform so that load transfer system is aligned properly. After the sample has been place on the loading platform, a small load should be applied in order to hold the sample in the appropriate position. In addition, it is important to ensure both upper and lower loading platform has full contact with the sample. Once the sample has been set up properly, the test can start with loading rate 0.25MPa√m/s or a load that can cause the sample to fail in first 20 second according to ISRM standard (Forwell, 1995). Also, unloading and reloading cycles is required to perform when it reaches 20% of the maximum load so that the sample and the loading platform can in perfect contact. Both maximum failure load and the vertical displacement should be recorded when the rock just reach the failure point and the error should be less than 1% and 0.001mm respectively. In addition, if the crack deviate from the notch plane more than 0.05D within 0.5D from the centre, the result should be deem as invalid (Fowell, 1995). When the test is finished, the geometrical dimension ($2a_o$) were measured for the use of calculating fracture toughness.

4. RISK MANAGEMENT PLAN

In order to complete the research successfully without any delay, the risks associated with the project have been identified and the corresponding mitigation is summarized as shown in Table 7. The risks rating as shown in Figure 9 is categorized into four categories – low, moderate, high, and extreme. They are categorized based the chance of occurrence for such event and the impact caused by the risk are categorized into five category – insignificant, minor, moderate, major, and catastrophic. The definition of the impact caused by the risk is summarised in Table 6.

Probability	Impact				
	Insignificant	Minor	Moderate	Major	Catastrophic
Certain (>90% chance)	High	High	Extreme	Extreme	Extreme
Likely (50%-90% chance)	Moderate	High	High	Extreme	Extreme
Moderate (10%-50% chance)	Low	Moderate	High	Extreme	Extreme
Unlikely (3%-10% chance)	Low	Low	Moderate	High	Extreme
Rare (<3% chance)	Low	Low	Moderate	High	High

Figure 9 Risk Rating Chart

Table 6
Definition of Impact.

Descriptor	Definition
Insignificant	Risk can be easily mitigated No Impact on project completion
Minor	Delays can up to 10% of schedule or additional cost incur up to 10% of budget Small impact on project quality
Moderate	Delays can up to 30% of schedule or additional cost incur up to 30% of budget Significantly impact on project quality
Major	Delays can up to 50% of schedule or additional cost incur up to 50% of budget Unable to complete the thesis
Catastrophic	Project abandoned

Table 7
Risk Management Plan.

Activities	Hazard	Possibility	Risk Rating	Impact	Control/Mitigation
Laboratory Set Up	Get electrocuted when setting up electronic equipment	Unlikely	Low	Insignificant	Be aware of exposed power cable and wear insulate glove when setting up the equipment
	Trip over by objects from the laboratory	Moderate	Low	Insignificant	Ensure all the objects are in place and tidy
Sample Preparation	Wrong dimension of samples	Likely	High	Moderate	Check the dimension and experiment procedures with supervisor
	Experiment cannot be conducted due to accidentally break the samples	Moderate	High	Moderate	Pay extra cautious when handling the samples and prepare the samples on a table with soft mat on
	Hurting yourself by tools when preparing samples (e.g electric saw, cutters, polisher)	Moderate	Low	Insignificant	Pay extra cautious when using those tools and wear PPE
	Inhale the dust created when cutting or polishing samples	Moderate	Low	Insignificant	Put mask on when cutting and polishing the rock samples
	Rock debris flies into eyes when cutting the samples	Moderate	Low	Insignificant	Wear safety glasses to prevent debris fly into eyes
Equipment Sep Up	Wrongly calibrated the equipment	Moderate	High	Moderate	Check with supervisor or calibrate the equipment under the supervision of supervisor

	Hurting yourself when moving heavy equipment	Unlikely	Low	Insignificant	Move heavy equipment with extra cautious or ask for assistant
	Equipment being stolen or damaged by extreme weather condition (e.g flooding)	Rare	High	Catastrophic	Place the equipment in a safe and covered area and lock it properly
	Power outrage	Unlikely	Low	Minor	Be prepared with backup power sources
	Equipment malfunction	Unlikely	High	Major	Ensure regular maintenance of the equipment
Experiment	Rock debris or pieces flying out from the machine when fracturing	Moderate	Low	Insignificant	Surround the machine with solid cover to prevent debris fly out and ensure there is a safe distance with the machine
Data Collection	Human errors (e.g misreading results)	Moderate	Low	Insignificant	Pay extra cautious when reading the results
	Loss of result or works	Moderate	Extreme	Major	Saving multiples backup on different devices such as USB drives, and university's computer
Completion of thesis	Poor communication with supervisor	Moderate	Extreme	Major	Consistent meeting should be set up to update the progress of work
	Poorly Interpretation of the results	Likely	High	Moderate	Communicate with supervisor to ensure the work is on track
	Insufficient referencing material	Moderate	Moderate	Moderate	Time management control in order to have sufficient amount of time for research

	Poor report structure and format, and grammatical errors	Moderate	Low	Insignificant	Check with supervisor to ensure the quality of report and thorough proof read before summation

5. CONTINGENCY PLAN

The hazards that have been previously identified in the last section have it corresponding control or prevention action. However if such hazards still happen even control measure have taken place, a contingency plan is necessary in order to provide an alternative approach to complete the project without delay. The contingency plan for its associated hazards is summarized in Table 8.

Table 8
Contingency Plan

Hazard	Possibility	Risk Rating	Consequence	Contingency Plan
Experiment cannot be conducted due to running out of budget	Moderate	High	Moderate	Slightly change the objective of thesis topic so that the research can continue with existing data
Loss of rock sample (e.g stolen or broken)	Likely	Extreme	Major	Use another type of rock sample that is available
Equipment being stolen or damaged by extreme weather condition (e.g flooding)	Unlikely	Extreme	Catastrophic	Search for another university that has the right equipment to run the test
Equipment malfunction or broken	Moderate	Extreme	Major	Search for another university that has the right equipment to run the test
Computer broke down	Rare	High	Catastrophic	Use others computer to finish the work

Technician who is responsible for setting up the experimental equipment is absence	Moderate	High	Moderate	Look for another technician or seek for assistance of supervisor
Program for image process does not work	Unlikely	Moderate	Moderate	Try it on another computer
Loss of all backup of the experimental data and works	Rare	High	Catastrophic	Retrieve them from google drive

6. RESULTS AND ANALYSIS

A series of fracture toughness test was conducted to sandstone and basalt under four different temperatures. The Chevron notched crack length were being measured once the experiment was finished and such value are summarized in Table 9, 10, and 11. In addition, the dimensionless parameters required for the calculation of fracture toughness are summarized in Table 12, 13, and 14 and such calculation can be found in Appendix C.

Table 9
Dimension of CCNBD Sample (Dry Sandstone)

Sample ID	Temperature (°C)	Initial Chevron notched crack length a_0 (mm)	Final Chevron notched crack length a_1 (mm)
S/CCNBD43	25	4.5	18.27
S/CCNBD1	25	5.3	18.885
S/CCNBD8	-25	5.4	18.995
S/CCNBD10	-25	5.9	18.715
S/CCNBD7	-50	5.5	18.94
S/CCNBD9	-50	5.0	18.68
S/CCNBD13	-75	6.5	18.97
S/CCNBD11	-75	6.6	18.7

Table 10
Dimension of CCNBD Sample (Wet Sandstone)

Sample ID	Temperature (°C)	Initial Chevron notched crack length a_0 (mm)	Final Chevron notched crack length a_1 (mm)
S/CCNBD14	25	4.8	18.415
S/CCNBD2	25	4.7	18.48
S/CCNBD4	-25	5.8	18.295
S/CCNBD3	-25	4.7	18.49
S/CCNBD12	-50	4.4	18.97
S/CCNBD5	-75	5.4	18.95
S/CCNBD6	-75	5.6	19.02

Table 11
Dimension of CCNBD Sample (Dry Basalt)

Sample ID	Temperature (°C)	Initial Chevron notched crack length a_0 (mm)	Final Chevron notched crack length a_1 (mm)
B/CCNBD2	25	5.5	18.845
B/CCNBD1	25	5.2	18.05
B/CCNBD4	-25	3.7	18.935
B/CCNBD3	-25	4.5	18.73
B/CCNBD7	-50	4.2	18.79
B/CCNBD6	-50	4.7	19
B/CCNBD8	-75	3.7	18.52
B/CCNBD5	-75	4.2	19

Table 12
Dimensionless Parameters (Dry Sandstone)

Sample ID	α_0	α_B	α_1	μ	v	Y_{min}
S/CCNBD43	0.169977	1.004584	0.697861	0.2574	1.7288	0.860138
S/CCNBD1	0.204829	1.030849	0.723702	0.25935	1.72512	0.903839
S/CCNBD8	0.207035	1.020837	0.726247	0.259678	1.7289	0.911463
S/CCNBD10	0.225548	1.021926	0.713632	0.2609	1.7268	0.894654
S/CCNBD7	0.212505	1.024166	0.726506	0.26	1.7267	0.911543
S/CCNBD9	0.191498	1.026427	0.715435	0.2587	1.7257	0.889176
S/CCNBD13	0.250287	1.023381	0.727099	0.2626	1.7277	0.922272
S/CCNBD11	0.253354	1.023381	0.71675	0.2628	1.7275	0.906489

Table 13
Dimensionless Parameters (Wet Sandstone)

Sample ID	α_0	α_B	α_1	μ	v	Y_{min}
S/CCNBD14	0.184347	1.035488	0.706503	0.25824	1.72396	0.872945
S/CCNBD2	0.178722	1.025641	0.707233	0.2578	1.7256	0.873568
S/CCNBD4	0.223989	1.027017	0.701092	0.2608	1.72664	0.875056
S/CCNBD3	0.179517	1.031837	0.709244	0.2579	1.7246	0.876323
S/CCNBD12	0.170311	1.024166	0.727656	0.25645	1.72547	0.900079
S/CCNBD5	0.207742	1.023381	0.726332	0.25973	1.7264	0.910125
S/CCNBD6	0.212725	1.019548	0.729015	0.26	1.7275	0.916035

Table 14
Dimension Parameters (Dry Basalt)

Sample ID	α_0	α_B	α_1	μ	v	Y_{min}
B/CCNBD2	0.211203	1.024362	0.723	0.26031	1.72655	0.907024
B/CCNBD1	0.200997	1.024166	0.692367	0.25929	1.726236	0.856741
B/CCNBD4	0.143407	1.034641	0.72897	0.2543	1.71688	0.888975
B/CCNBD3	0.172229	1.022166	0.71845	0.2575	1.7256	0.889605
B/CCNBD7	0.15957	1.034852	0.720752	0.2569	1.7278	0.892478
B/CCNBD6	0.180534	1.031985	0.725191	0.25798	1.7228	0.899861
B/CCNBD8	0.142583	1.043378	0.709851	0.256195	1.7	0.856355
B/CCNBD5	0.162131	1.036378	0.728248	0.25704	1.7211	0.900203

Based on the result obtained, the dimensionless parameter, α_1 and α_B , were plotted against each other for each sample to check the validity of the results. As shown in Figure 10, all the results are within the geometrical range proposed by ISRM therefore all the fracture toughness tests for sandstone and basalt were valid.

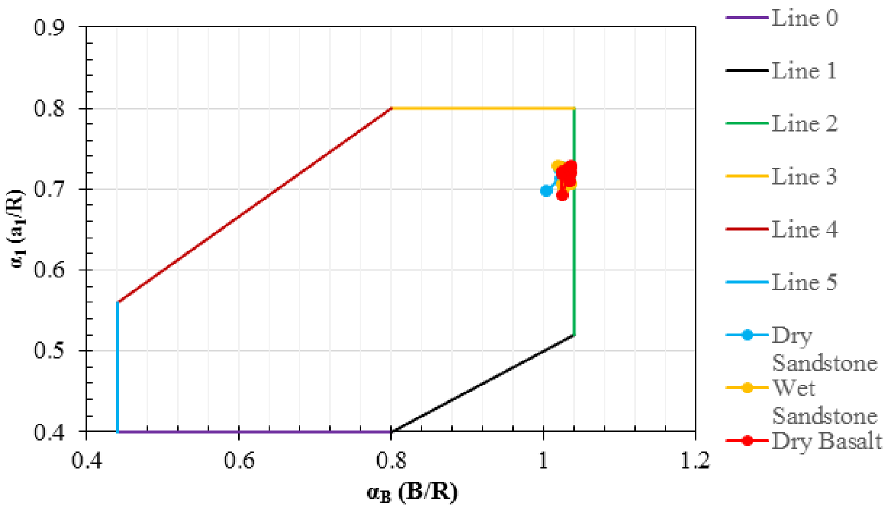

Figure 10. Valid Geometrical Range

The maximum failure load for both dry and wet samples was being recorded for the calculation of fracture toughness and such values are summarized in Table 15, 16, and 17. In addition, the CCNBD samples after the experiment and the result of plotting force against displacement can be found in Appendix B. The result of dry sandstone according to Table 15 shows that there is a general increase trend of both failure load and fracture toughness as temperature decreases. The average minimum failure load was found to be approximately 2.6kN while the average maximum failure load was approximately 3.11kN. However, unexpected results occur at -50^{o}C. Both failure load and fracture toughness was observed to have 20% drops. Such drop could be due to human error which did not freeze the sample for sufficient time or the temperature of sample was affected by ambient temperature so that the strength of the rock sample was not representing the strength at -50 ^{o}C. In addition, the averaged minimum fracture toughness was approximately 0.55 $\mathbf{MPa\sqrt{m}}$ and the average maximum fracture toughness was 0.66$\mathbf{MPa\sqrt{m}}$.

The result of wet sandstone as shown in Table 16 also shows a similar result as expected. Both failure load and fracture toughness increases as temperature decreases. The average minimum failure load was 2.2kN and the maximum failure load was 6.89kN. In addition, the average minimum fracture toughness was 0.44 $\mathbf{MPa\sqrt{m}}$ and the maximum was 1.46 $\mathbf{MPa\sqrt{m}}$.

The result of dry basalt as shown in Table 17 shows that both failure load and fracture toughness increases as temperature decreases but with the magnitude higher than sandstone. The average minimum failure load was 8.51kN and the maximum failure load was 9.69kN. In addition, the average minimum fracture toughness was 1.74$\mathbf{MPa\sqrt{m}}$ and the maximum was 1.93$\mathbf{MPa\sqrt{m}}$.

Table 15
Result of Dry Sandstone

Temperature	Sample	Failure Load (kN)	Average Failure Load (kN)	Fracture Toughness ($\mathbf{MPa\sqrt{m}}$)	Average Fracture Toughness ($\mathbf{MPa\sqrt{m}}$)
25 ^{o}C	S/CCNBD43	2.9	2.65	0.59	0.55
	S/CCNBD1	2.39		0.50	
-25 ^{o}C	S/CCNBD8	3.39	3.29	0.72	0.69
	S/CCNBD10	3.19		0.66	
-50 ^{o}C	S/CCNBD7	2.49	2.62	0.53	0.55
	S/CCNBD9	2.75		0.57	
-75 ^{o}C	S/CCNBD13	2.89	3.11	0.62	0.66
	S/CCNBD11	3.33		0.70	

Table 16
Results of Wet Sandstone

Temperature	Sample	Failure Load (kN)	Average Failure Load (kN)	Fracture Toughness (**MPa√m**)	Average Fracture Toughness (**MPa√m**)
25 °C	S/CCNBD14	2.18	2.20	0.44	0.44
	S/CCNBD2	2.22		0.44	
-25 °C	S/CCNBD4	6.25	6.17	1.26	0.48
	S/CCNBD3	6.08		1.22	
-50 °C	S/CCNBD12	6.34	6.34	1.32	1.32
-75 °C	S/CCNBD5	6.86	6.89	1.45	1.46
	S/CCNBD6	6.91		1.47	

Table 17
Result of Dry Basalt

Temperature	Sample	Failure Load (kN)	Average Failure Load (kN)	Fracture Toughness (**MPa√m**)	Average Fracture Toughness (**MPa√m**)
25 °C	B/CCNBD2	8.50	8.51	1.79	1.74
	B/CCNBD1	8.52		1.69	
-25 °C	B/CCNBD4	8.87	8.89	1.86	1.83
	B/CCNBD3	8.90		1.79	
-50 °C	B/CCNBD7	9.33	9.53	1.83	1.91
	B/CCNBD6	9.73		1.98	
-75 °C	B/CCNBD8	9.86	9.69	1.91	1.93
	B/CCNBD5	9.51		1.94	

7. DISCUSSION

7.1. EFFECT OF TEMPERATURE AND WATER ON SANDSTONE

Based on the results as shown in Table 15, 16, and 17, the average maximum load and average fracture toughness was being plotted against temperature so that the effect of temperature on the property of rock can be observed. The relationship between failure load and temperature, and fracture toughness and temperature for sandstone is illustrated in Figure 11 and 12 respectively. In addition, the percentage change of failure load in wet condition relative to dry condition is illustrated in Figure 13. As shown in Figure 11, it can be clearly seen that failure load increases as temperature decreases. Not surprisingly fracture toughness also increases as temperature decreases since fracture toughness is directly proportion to failure load. However, at room temperature the failure load in wet condition is lower than dry condition by about 20% as shown in Figure 13. Such result is similar to what Price (1960) has obtained as mentioned in section 2.2.1 which has 19% drop of failure load at room temperature if sample is saturated. The reason of this behaviour is because the water weakens the rock sample by penetrating through the pre-existing microcracks which enlarge the microcracks that presents in the rock sample. As a result the strength of wet sample is lower than dry sample at room temperature.

The effect of temperature starts to be significant when temperature reach down to below 0 ^{o}C as the sample would be frozen at this point. When rock is frozen the pore water in the wet sample will change to ice. During this process, pore water pressure that was exerting to the rock will be substituted to ice pressure due to the volume expansion of ice when it changes from liquid to solid state. The increase in volume of ice can be up to 10% (Dwivedi, Soni and Geo, 2000). Such process could create new cracks and hence weaken the strength of the rock sample. However, if there is space inside the rock that allows the volume expansion of ice is available, new cracks would not be developed due to the expansion of ice and hence would not weaken the rock sample. In fact, the results show that ice did not weaken the sample but increase the strength of rock instead as temperature decreases. As temperature decreases the strength of ice will contribute to the strength of rock and hence increase the strength of rock. In addition, the increases in strength can up to 120% when temperature reaches -75 ^{o}C as shown in Figure 13 which is similar to the result of Mellor (1973) as discussed in section 2.3. One more observation can be seen from the graph is temperature has greater effect to wet sample as the increase rate of both failure load and fracture toughness is faster than dry sample which illustrated as shown in the yellow trend line as shown in Figure 11 and 12. This is simply because the ice content of wet sample is more than in dry sample and hence the strength of ice enhance the rock strength significantly when temperature decreases. In addition, the relationship between wet fracture toughness and temperature can be expressed in logarithmic a relationship while the relationship between dry fracture toughness and temperature is only a linear relationship as shown in Figure 12.

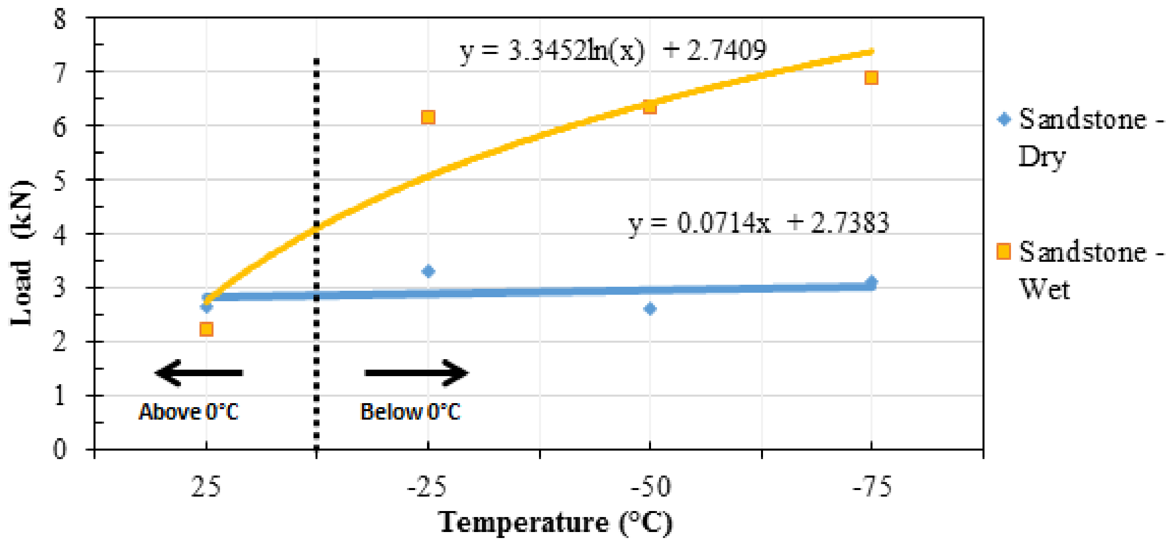

Figure 11. Load vs. Temperature

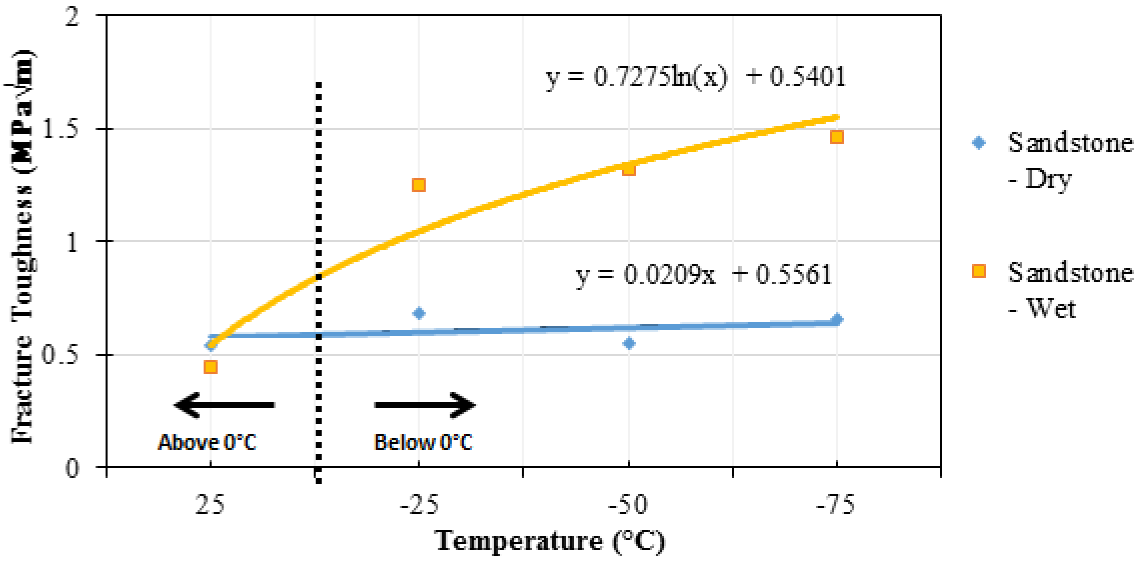

Figure 12. Fracture Toughness vs. Temperature

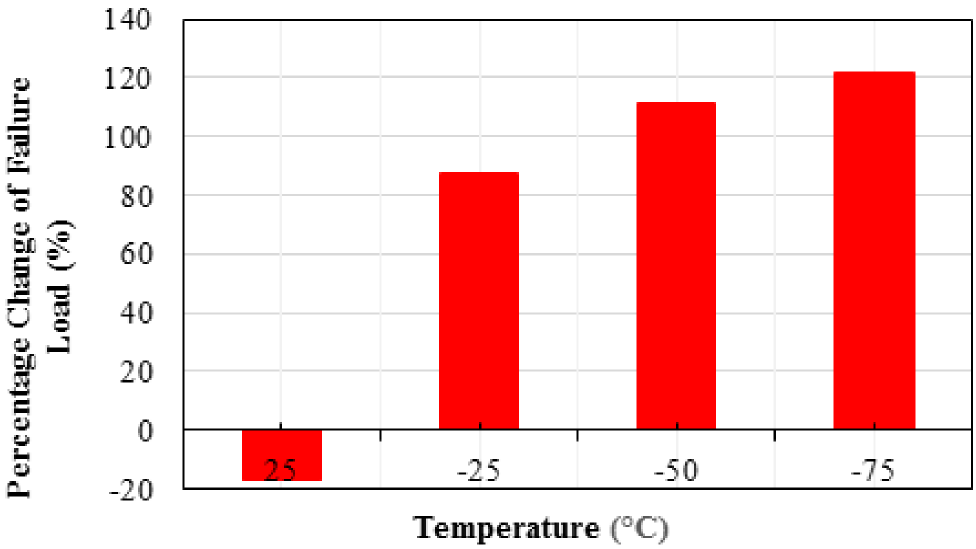

Figure 13. Percentage Change of Failure Load vs. Temperature

7.2. Effect of Temperature On Basalt

The relationship between failure load and temperature, and fracture toughness and temperature for basalt is illustrated in Figure 14 and 15 respectively. In addition, the percentage change of failure load relative to room temperature (25°C) in dry condition is illustrated in Figure 16. As shown in Figure 14 and 15, both failure load and fracture toughness increases as temperature decreases. The increasing rate of failure load and temperature can be perfectly fit into a linear relation. As the temperature reduce down below 0 °C, mineral grains within the rocks start to shrink which produce a confining stress to the sample and hence increases the compressive strength to the rock sample. Apart from the confining stress that contributes to the strength of rock, it is also possible that a small portion of moisture could still capture within the rock even the sample were in dry condition and hence when the moisture changes to ice the strength of rock increases. The maximum increases of strength could up to 14% when temperature reaches -75°C while the minimum was 7% when temperature was at -25°C as shown in Figure 16.

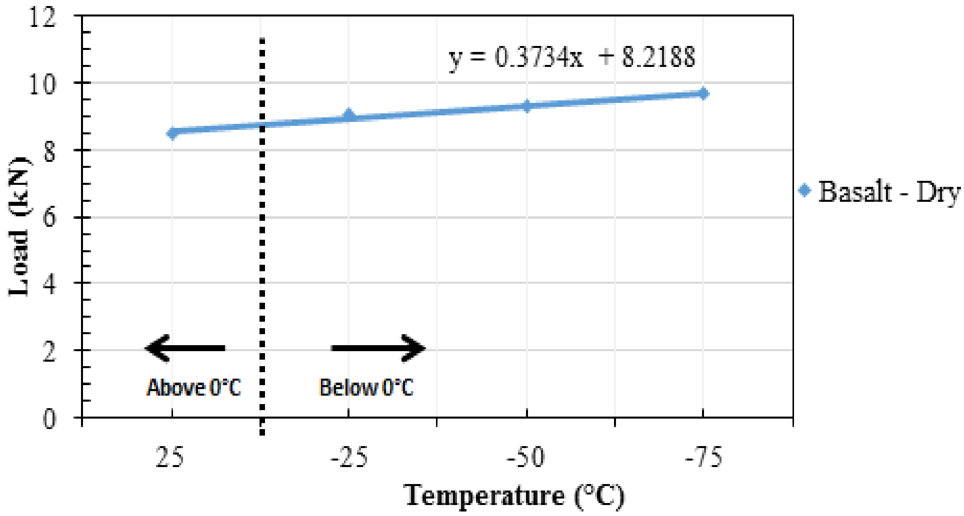

Figure 14. Load vs. Temperature

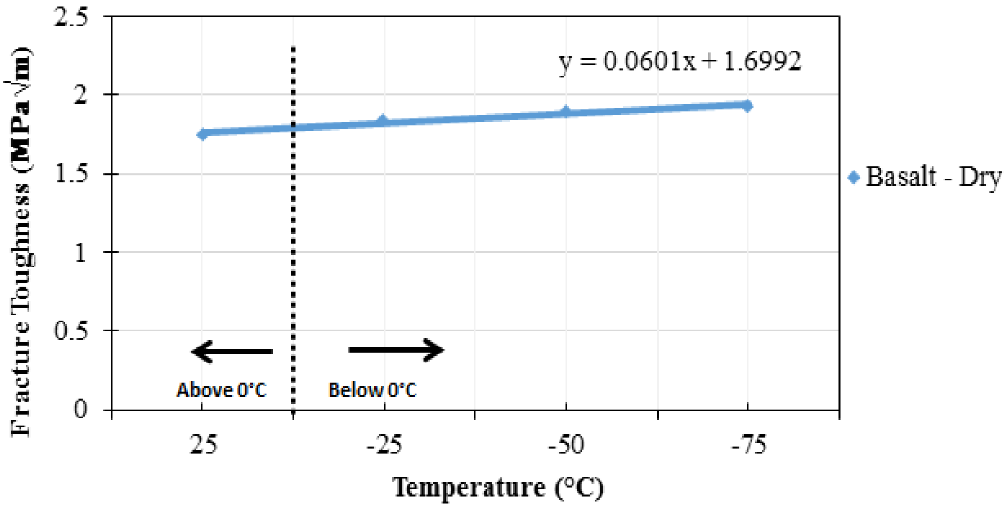

Figure 15. Fracture Toughness vs. Temperature

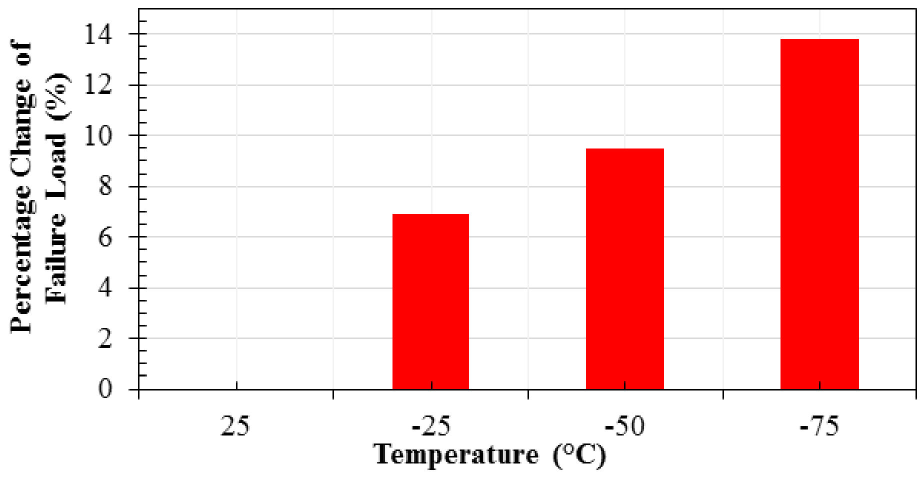

Figure 16. Percentage Change of Failure Load vs. Temperature

7.3. Effect of Temperature on Sandstone and Basalt

Comparison is made between sandstone and basalt. As shown in Figure 17 and 18, the failure load and the fracture toughness of basalt is higher than sandstone under any temperature as basalt is a harder rock compare to sandstone. The maximum difference of failure load between them is up to 6.5% and the minimum is about 5.8% as shown in Figure 19. Also, temperature does not have much effect on dry rocks as only small increases of failure load and fracture toughness can be observed for both samples as temperature decreases.

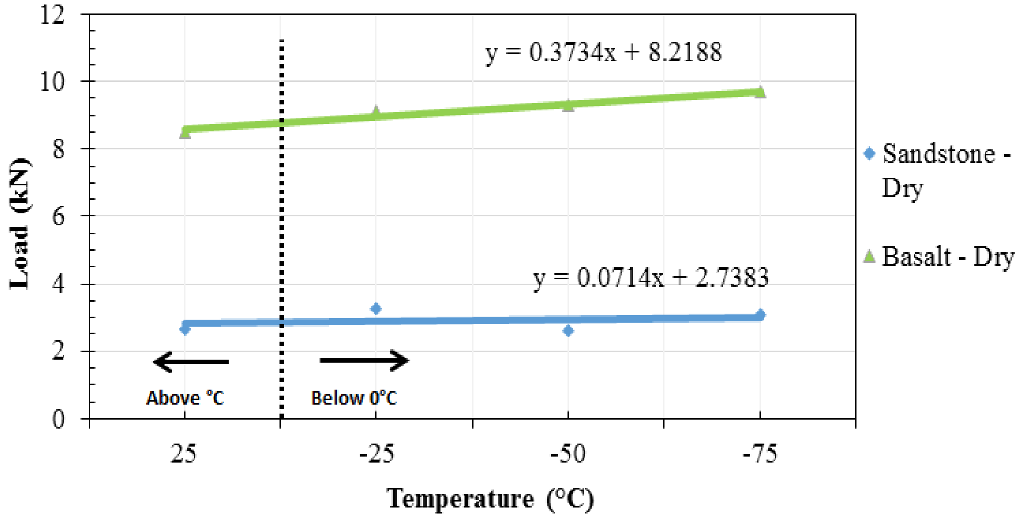

Figure 17. Load vs. Temperature

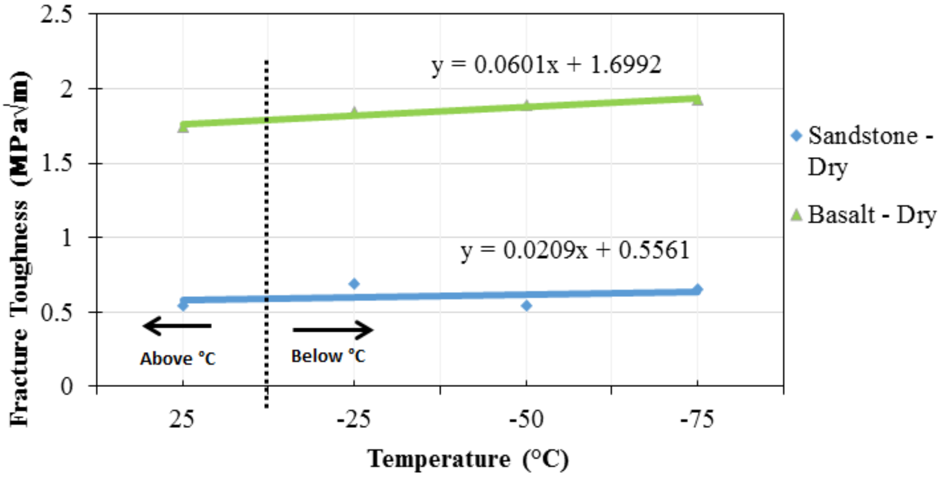

Figure 18. Fracture Toughness vs. Temperature

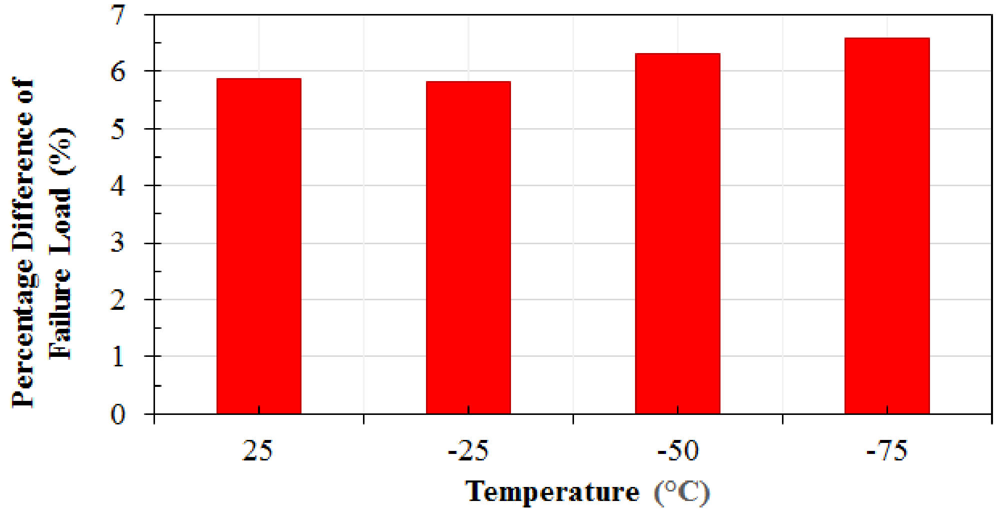

Figure 19. Percentage Change of Failure Load vs. Temperature

8. CONCLUSIONS

This research sought to investigate the combine effect of water and temperature on the mechanical properties of rock. To examine this, fracture toughness test was conducted in dry and wet condition under sub-zero temperature by testing both soft and hard rock (Sandstone and Basalt).

One of the key findings shows that the strength of both rock samples, sandstone and basalt, increases when temperature decreases down to below 0^0C. The fracture toughness for dry sandstone and dry basalt at room temperature was 0.55$\mathbf{MPa\sqrt{m}}$ and 1.74$\mathbf{MPa\sqrt{m}}$ respectively, while the failure load of dry sandstone and dry basalt at -75^0C was 0.66$\mathbf{MPa\sqrt{m}}$ 1.93 $\mathbf{MPa\sqrt{m}}$. Such increase was due to shrinkage of the grains within the rock which generate a confining stress to the rock sample and hence increase in strength.

Moreover, the effect of water on the properties of rocks was found to be different under different temperature. The fracture toughness of wet sandstone was found to be lower at room temperature (25^0C) relative to dry sandstone and such value was 0.44 $\mathbf{MPa\sqrt{m}}$ and 0.55 $\mathbf{MPa\sqrt{m}}$ respectively. The reduction in strength is due to the weakening effect caused by water. However, when temperature decreases down to below 0^0C the fracture toughness of wet sandstone was found to be higher relative to dry sandstone. The differences in strength can up to 120% when temperature is at -75^0C. Also, it is important to note that wet sample is more sensitive to the change in temperature as wet sample contain more ice content relative to dry sample. When temperature drop below 0^0C pore water will be frozen and hence increases the strength of rock significantly. In addition, the relationship between wet fracture toughness and temperature was found to be a logarithmic relationship, while the relationship between dry fracture toughness and temperature was only a linearly relationship.

In addition, the fracture toughness of basalt is found to be larger than sandstone. The maximum difference of failure load between basalt and sandstone could up to 6.5% and the minimum could up to 5.8% as basalt is a harder rock.

9. RECOMMENDATIONS

One unexpected result for dry sandstone that was conducted at temperature -50^{0}C was observed. An unexpected decrease of failure load was found under that temperature and it was suspected to be caused by either human error or the influence of ambient temperature to the frozen sample. To reduce the chance of occurrence of such error one of the recommendations is to conduct the test inside the environmental chamber thus the sample temperature can be kept constant and in a control condition which would not be affected by ambient temperature. Besides, more rock types and smaller range of temperature for instance the test should be done at every 10 degree instead of every 25 degree is recommended so more accurate result can be obtained and a wider range of rock types are covered. Also, different size of rock can be introduced into the experiment so that the effect of temperature on the size of rock can be investigated. In addition, further investigation can be focus on the relationship between temperature and discontinuity by testing rock samples with different types of defect.

Moreover, to further investigate the effect of temperature and water to the properties of rocks CT scan technique can be introduced to the study. The implementation of CT scan can help to look at the fracture process that occur within the rock so that mechanical properties of rock under low temperature can be evaluated such as fracture distribution, fracture density, and the pattern of fracturing which could provide better understanding of rock fracturing process. Also, numerical modelling can be introduced to the study as well. As the prediction of the rock mass behaviour under sub-zero temperature can be made in comparison to experimental results.

10. REFERENCES

Backers, T, 2004. Fracture toughness determination and micromechanics of rock under mode I and mode II loading. PhD thesis (unpublished), University of Potsdam, Germany.

Bieniawski, Z T, 1967. Mechanism of brittle rock fracture Part I: Theory of the fracture process, *International Journal of Rock Mechanics and Mining Sciences & Geomechanical Abstracts*, 4(4): 395–406. Available from: < http://www.sciencedirect.com > [Accessed: 1 May 2016].

Bobet, A, 2000. The initiation of secondary cracks in compression [online], *Engineering Fracture Mechanics*, 66(2):187-219. Available from: < http://www.sciencedirect.com > [Accessed 6 May 2016].

Burshtein, L S,1969. Effect of moisture on the strength and deformability of sandstone, *Soviet Mining Science Journal*, 5(5):573-576.

Clark, G, 1987. *Principle of Rock Fragmentation*, pp 27-32 (Wiley and Sons: New York).

Collback, P S B, and Wiid, B L, 1965. *The influence of moisture content on the compressive strength*, 10p (National Mechanical Engineering Research Institute: Durgapur). Availabe from: < https://books.google.com.au/books > [Accessed: 5 May 2016].

Deliac, E P, 1986. Optimization des machines D'adattage a pics, PhD thesis (unpublished), University of Paris, Paris. Available from: < https://theses.lib.vt.edu > [Accessed: 16 June 2016].

Donovan, J G, 2003. Fracture toughness based models for the prediction of power consumption product size and capacity of jaw crushers, PhD thesis (unpublished), Virginia Polytechnic Institute, Blacksburg. Available from: <https://theses.lib.vt.edu> [Accessed: 16 June 2016].

Dowling, N E, 1999. *Mechanical Behaviour of Materials – Engineering Methods for Deformation Fracture and Fatigue*, 105p (Prentice Hall: Upper Saddle River).

Dwivedi, R D, Soni, A K, and Geo, A K, 2000. Fracture toughness of rock under sub zero temperature conditions [online], *International Journal of Rock Mechanics and Mining Science,* 37(1):1267-1275. Available from: < https://www.researchgate.net > [Accessed:12 June 2016].

Dyke, C G, and Dobereiner, L, 1991. Evaluating the strength and deformability of sandstone, *Engineering Geology & Hydrogeology*, 24(1):123-134.

Eberhardt, E, Stead, D, Stimpson, B and Read, R S, 1998. Identifying crack imitation and propagation thresholds in brittle rock [online], *Canadian Geotechnical Journal*, 35:222-233. Available from: < https://www.eoas.ubc.ca > [Accessed: 1 May 2016].

Ergular, Z A, and Ulusay, R, 2009. Water induced variations in mechanical properties of clay bearing rocks, *International Journal of Rock Mechanic and Mining Science*, 46(2):355-370.

Fowell, R J, 1995. Suggested method for determining mode 1 fracture toughnes using cracked chevron notched Brazilian disc specimens. *International Society for Rock Mechanics*, 32(1): 57-64.

Ghamgosar, M and Erarslan, N, 2014. The effect of cyclic loading amplitude and notch crack inclination angle on the fracture toughness test on Brisbane tuff-multiple factorial analyses, paper presented to ISRM European Regional Symposium on Rock Engineering and Rock Mechanics Structures in and on Rock Masses, 26-28 May [online]. Available from: < http://espace.library.uq.edu.au/view/UQ:332723 > [Accessed: 15 May 2016].

Ghamgosar, M and Erarslan, N, 2015. Experimental and numerical studies on development of fracture process zone (FPZ) in rocks under cyclic and static loadings [online], .*Rock Mechanics and Rock Engineering*, 49(3): 893-908. Available from: < http://espace.library.uq.edu.au/view > [Accessed: 8 May 2016].

Guo, H, Aziz, N I, and Schmidt, L C, 1993. Rock fracture toughness determination by the Brazilian test [online], *Engineering Geology*, 33(3): 177-188. Available from: < http://www.sciencedirect.com > [Accessed: 8 May 2016].

Hawkins, A B, and McConnell, B J, 1992. Sensitivity of sandstone strength and deformability to changes in moisture content, *Engineering Geology*, 25(2):115-130.

Hoek, E and Bieniawski, Z T, 1984. Brittle rock fracture propagation in rock under compression [online], *International Journal of Fracture Mechanics*, 1(3):137-155. Available from: < https://www.rocscience.com/documents/hoek/references/H1965B.pdf > [Accessed: May 2016].

Jiang, Q, Cui, J, Feng, X, and Jiang, Y, 2014. Application of computerized tomographic scanning to the study of water-induced weakening of mudstone, *Engineering Geology Environment*, 73(4):1293-1301.

Kessler, D, Insley, H, and Sligh, W, 1940. Physical mineralogical and durability studies on the building and monumental granites of the United States, *Journal of Research of the National Bureau of Standards*, 24:161-206.

Mellor, M, 1973. Mechanical properties of rocks at low temperatures, paper presented to 2nd International Conference on Permafrost, Yakutsk, 13-28 July [online]. Available from: < http://orbit.dtu.dk/fedora/ > [Accessed: 5 June 2016].

Ojo, O, and Brook, N, 1990. The effect of moisture on some mechanical properties of rock, *Mining Science and Technology*, 10(2):145-156.

Price, N J, 1960. The compressive strength of coal measure rocks [online], *Colliery Engineer*, 37(437):283-292. Available from: < https://books.google.com.au/books > [Accessed: 4 June 2016].

Ruiz, M D, 1966. Some technological of twenty six characteristics Brazilian rock types, Lisbon, 25 September – 1 October [online]. Available from: < https://www.onepetro.org > [Accessed: 1 June, 2016].

Sagong, M and Bobet, A, 2002. Coalescence of multiple flaws in rock model material in uniaxial compression [online], *International Journal of Rock Mechanics and Mining Science*, 39(2):229-241. Available from: < http://www.sciencedirect.com > [Accessed 2 May 2016].

Tang, C A, Lin P, Wong, R H C and Chau, K T, 2001. Analysis of crack coalescence in rock like materials containing three flaws – Part II: numerical approach [online], *International Journal of Rock Mechanics and Mining Science*, 38(7):925-939. Available from: < http://www.sciencedirect.com > [Accessed: 2 May 2016].

Van Eeckhout, E M, 1976. Mechanism of strength reduction due to moisture in coal mine shales [online], *International Journal of Rock Mechanics and Mining Science*, 13(2): 61-67. Available from: < https://www.researchgate.net/publication > [Accessed: 20 Jun 2016].

Vasarhelyi, B, 2003. Some observation regarding the strength and deformability of sandstones in case of dry and saturated conditions, *Engineering Geology Environment, 62(1):245-249.*

Whittaker, B N, Singh, R N and Sun, G, 1992. *Rock fracture mechanics principal, design and applications*, 226p (Amsterdam: Elsevier). Available from: < https://books.google.com.au > [Accessed: 10 May 2016].

Yamabe, T and Neaupane, K M, 2001. Determination of some thermos mechanical properties of Sirahama sandstone under subzero temperature condition [online], *International Journal of Rock Mechanics and Mining Science,* 31(1):1029-1034. Available from: < http://www.sciencedirect.com > [Accessed: 20 June 2016].

11. APPENDIX

11.1. APPENDIX A: CCNBD SAMPLE

Figure 20. CCNBD Sample (Basalt)

Figure 21. CCNBD Sample (Dry Sandstone)

Figure 22. CCNBD Sample (Wet Sandstone)

11.2. Appendix B: CCNBD Sample After Test

Figure 23. CCNBD Sample of Basalt after Experiment (Left: 25C and Right: -25C)

Figure 24. CCNBD Sample of Basalt after Experiment (Left: -50C and Right: -75C)

Figure 25. CCNBD Sample of Wet Sandstone after Experiment (Left: 25C and Right: -25C)

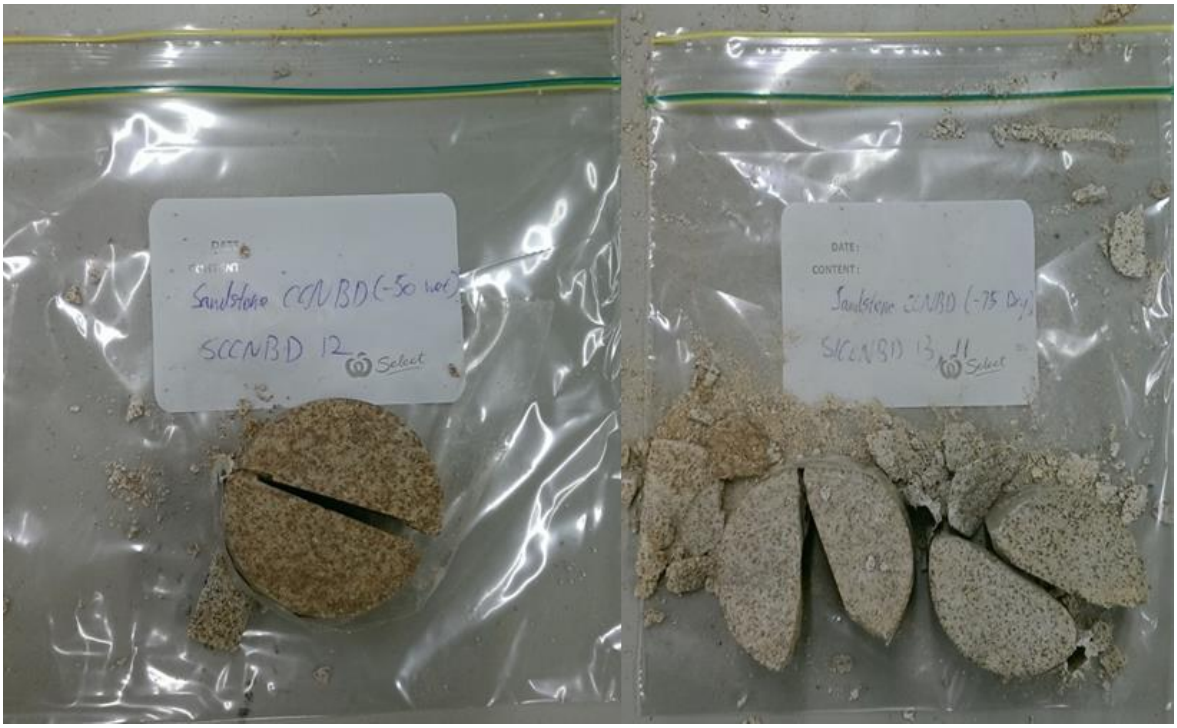

Figure 26. CCNBD Sample of Wet Sandstone after Experiment (Left: -50C and Right: -75C)

Figure 27. CCNBD Sample of Dry Sandstone after Experiment (Left: 25C and Right: -25C)

Figure 28. CCNBD Sample of Dry Sandstone after Experiment (Left: -50C and Right: -75C)

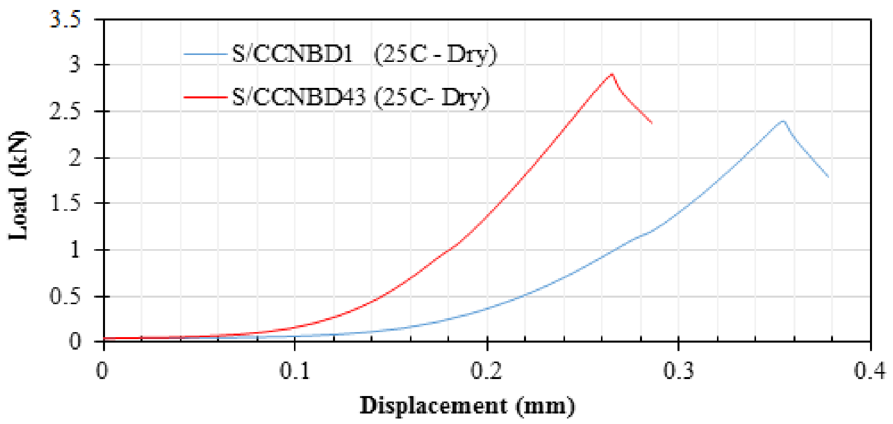

Figure 29. Result of Dry Sandstone (25C)

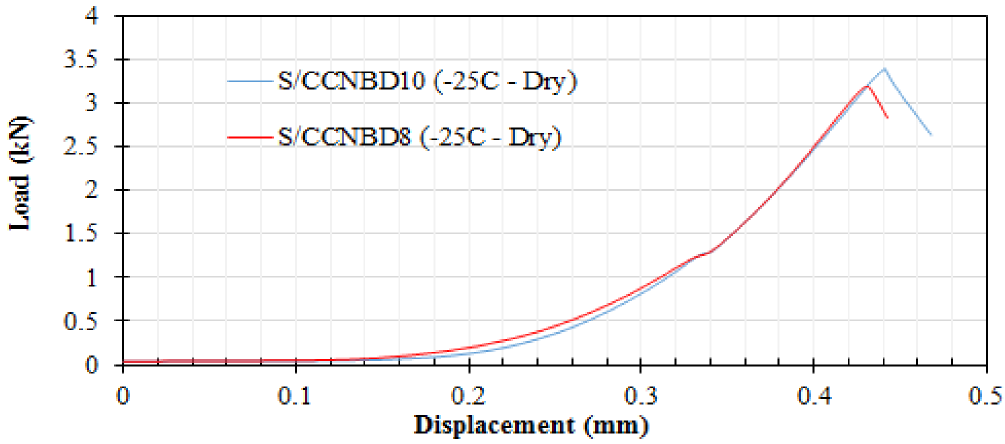

Figure 30. Result of Dry Sandstone (-25C)

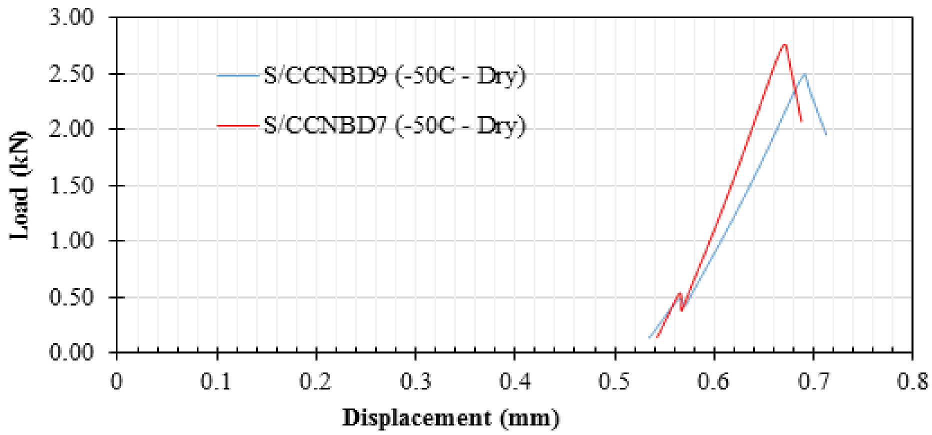

Figure 31. Result of Dry Sandstone (-50C)

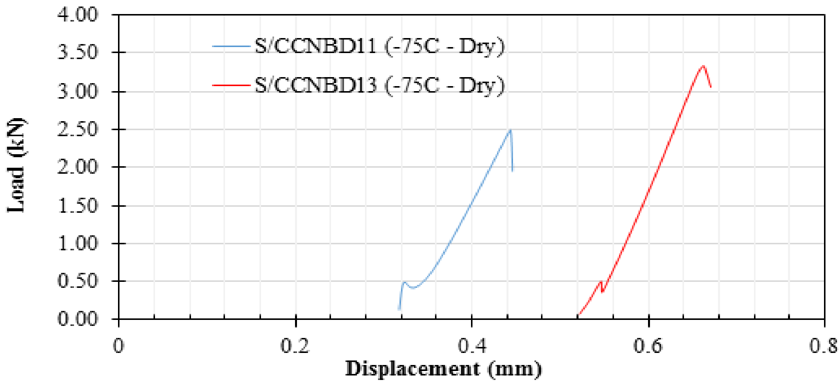

Figure 32. Result of Dry Sandstone (-75C)

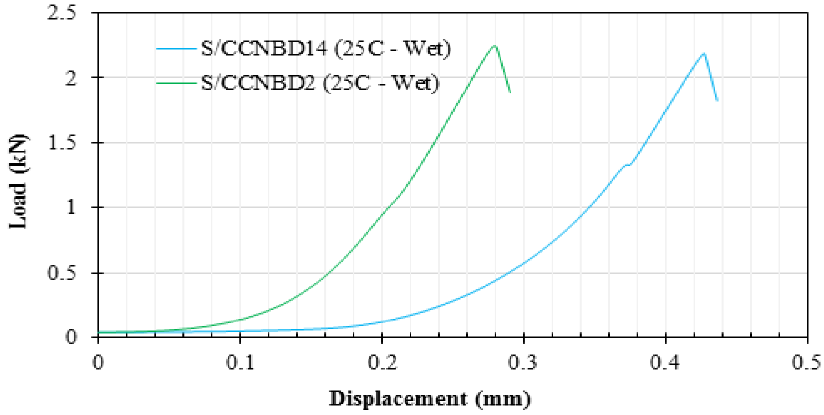

Figure 33. Result of Wet Sandstone (25C)

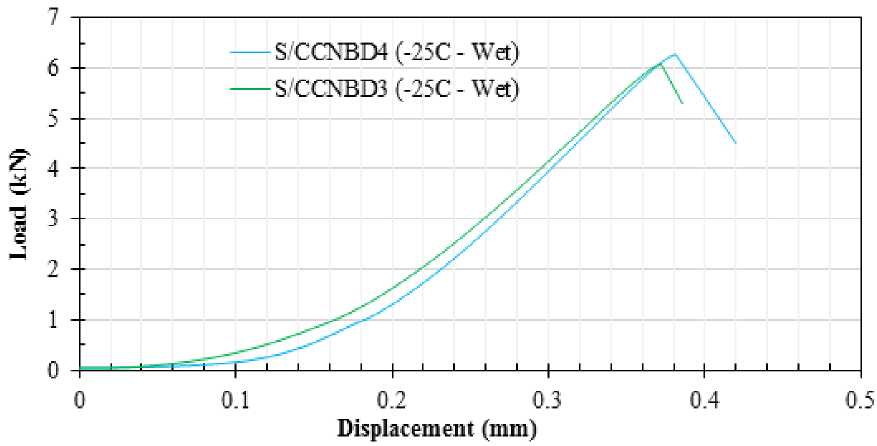

Figure 34. Result of Wet Sandstone (-25C)

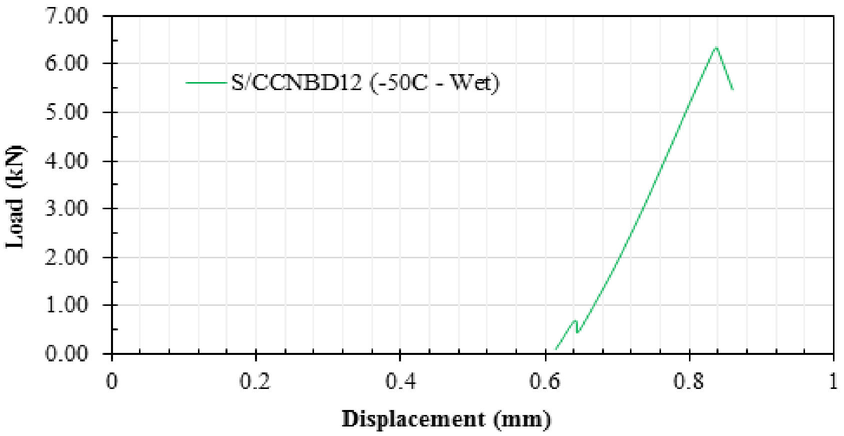

Figure 35. Result of Wet Sandstone (-50C)

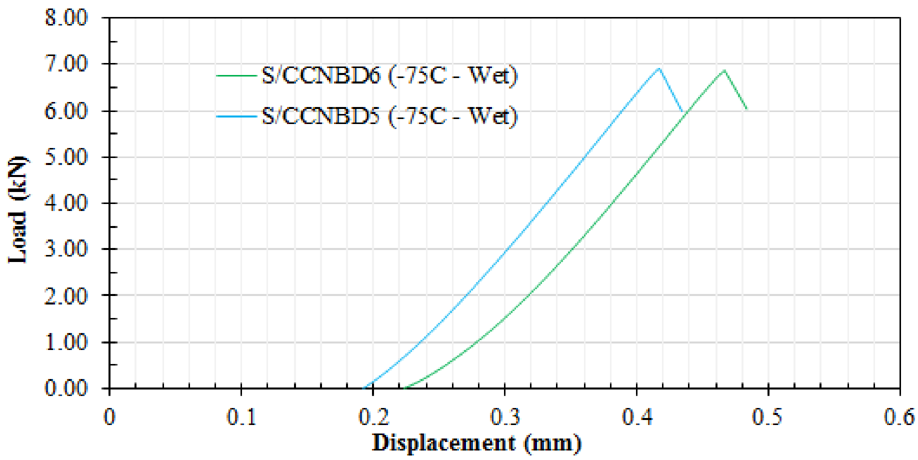

Figure 36. Result of Wet Sandstone (-75C)

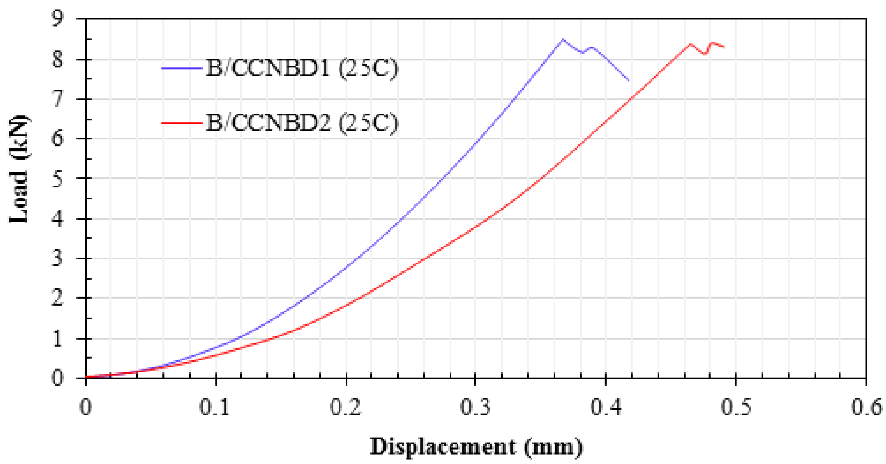

Figure 37. Result of Dry Basalt (25C)

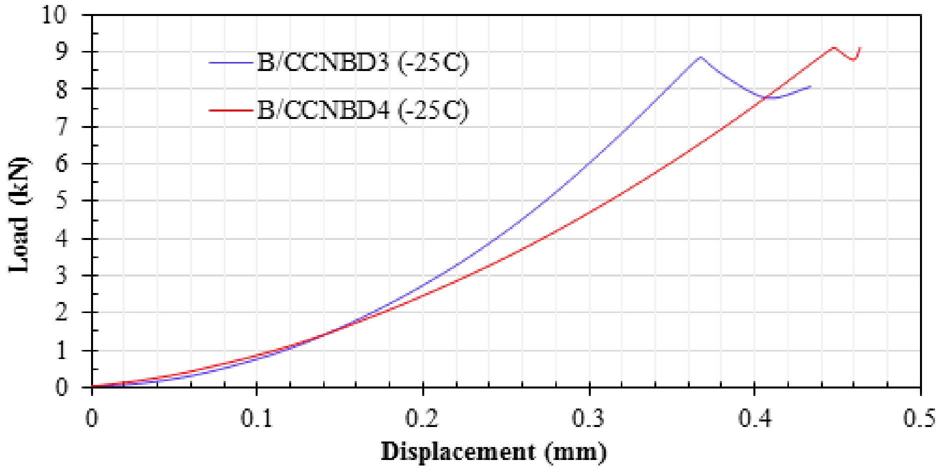

Figure 38. Result of Dry Basalt (-25C)

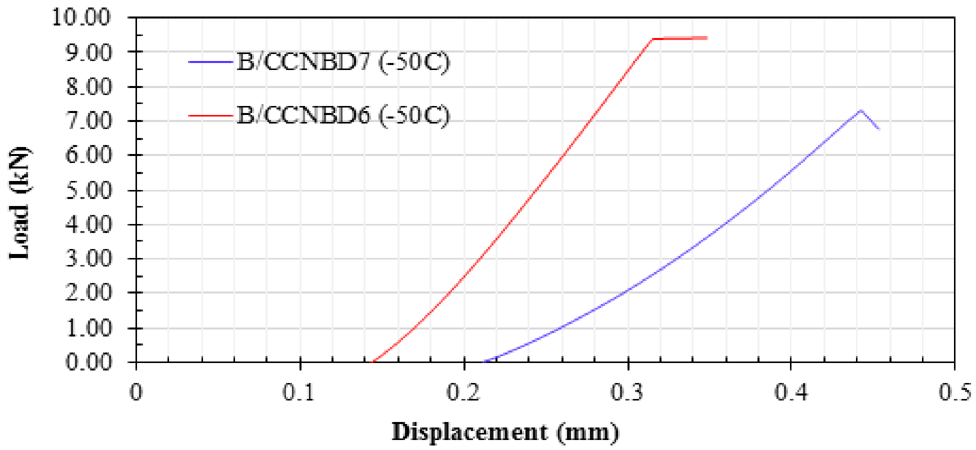

Figure 39. Result of Dry Basalt (-50C)

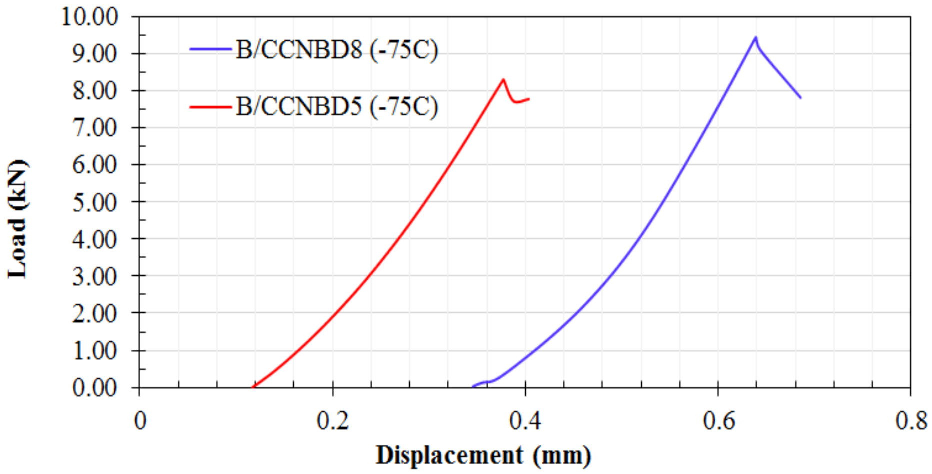

Figure 40. Result of Dry Basalt (-75C)

11.3. Appendix C: Calculation of Dimensionless Parameters and Fracture Toughness

The following demonstration is taking S/CCNBD43 as an example. Such calculation applies to all of the samples. The parameter α_0 (a_0/R) and α_B (B/R) was found to be 0.169977 and 1.004584 respectively. According to Figure 41 as shown, both α_0 and α_B does not match to any number therefore to find parameter μ and v interpolation is required. The first step is to apply interpolation along y-axis (α_B). Once a value is obtained from y-axis, second interpolation can then be applied along x-axis (α_0). Such calculations are illustrated as follow:

For μ:

Interpolation along y-axis

$$\mathrm{y} = y_1 + \left(\frac{y_2 - y_1}{x_2 - x_1}\right)(\mathrm{x} - x_1)$$

$$y = 0.2564 + (\frac{0.2565 - 0.2564}{1.04 - 1})(1.004584 - 1)$$

$$= 0.25641146$$

Interpolation along x-axis

$$\mathrm{y} = y_1 + \left(\frac{y_2 - y_1}{x_2 - x_1}\right)(\mathrm{x} - x_1)$$

$$y = 0.2564 + (\frac{0.2576 - 0.2565}{0.2576 - 0.2564})(0.25641146 - 0.2564)$$

$$= 0.2574$$

For v:

Interpolation along y-axis

$$y = y_1 + \left(\frac{y_2 - y_1}{x_2 - x_1}\right)(x - x_1)$$

$$y = 1.7279 + (\frac{1.7213 - 1.7279}{1.04 - 1})(1.004584 - 1)$$

$$= 1.652264$$

Interpolation along x-axis

$$y = y_1 + \left(\frac{y_2 - y_1}{x_2 - x_1}\right)(x - x_1)$$

$$y = 1.7213 + (\frac{1.7231 - 1.7213}{1.73 - 1.7279})(1.652264 - 1.7279)$$

$$= 1.7288$$

Hence

$$Y_{min} = \mu e^{v\alpha_1}$$

$$= 0.2574e^{1.7288(0.697861)}$$

$$= 0.860138$$

Therefore the fracture toughness is 0.55 **MPa√m.**

$$K_{IC} = \frac{P_{max}}{B\sqrt{R}}Y_{min}$$

$$= \frac{2.65}{26.3\left(\sqrt{26.2}\right)}(0.860138)$$

$$= 0.55$$

α_0	0.100	0.150	0.175	0.200	0.225	0.250	0.275	0.300	0.325	0.350	0.375	0.400	0.425	0.450
							u							
α_B														
0.440	0.2747	0.2774	0.2791	0.2808	0.2825	0.2844	0.2865	0.2883	0.2914	0.2943	0.2979	0.3024	0.3069	0.3120
0.480	0.2727	0.2752	0.2765	0.2782	0.2795	0.2812	0.2833	0.2856	0.2882	0.2918	0.2954	0.2994	0.3039	0.3090
0.520	0.2708	0.2727	0.2740	0.2757	0.2771	0.2788	0.2806	0.2828	0.2857	0.2887	0.2925	0.2968	0.3013	0.3060
0.560	0.2689	0.2705	0.2716	0.2733	0.2744	0.2763	0.2781	0.2805	0.2831	0.2867	0.2901	0.2943	0.2989	0.3039
0.600	0.2667	0.2684	0.2696	0.2709	0.2721	0.2739	0.2757	0.2782	0.2812	0.2844	0.2882	0.2921	0.2967	0.3015
0.640	0.2649	0.2665	0.2674	0.2685	0.2701	0.2719	0.2738	0.2764	0.2791	0.2825	0.2863	0.2905	0.2947	0.2992
0.680	0.2632	0.2646	0.2655	0.2667	0.2682	0.2704	0.2718	0.2744	0.2774	0.2807	0.2848	0.2888	0.2930	0.2971
0.720	0.2611	0.2628	0.2637	0.2650	0.2667	0.2683	0.2705	0.2727	0.2763	0.2794	0.2831	0.2871	0.2916	0.2954
0.760	0.2598	0.2612	0.2625	0.2637	0.2650	0.2668	0.2693	0.2719	0.2744	0.2781	0.2819	0.2860	0.2895	0.2934
0.800	0.2582	0.2602	0.2611	0.2625	0.2641	0.2657	0.2680	0.2706	0.2736	0.2772	0.2811	0.2845	0.2878	0.2916
0.840	0.2572	0.2586	0.2599	0.2612	0.2628	0.2649	0.2672	0.2699	0.2727	0.2763	0.2801	0.2831	0.2867	0.2891
0.880	0.2562	0.2578	0.2593	0.2602	0.2621	0.2642	0.2668	0.2691	0.2723	0.2754	0.2793	0.2816	0.2853	0.2867
0.920	0.2553	0.2572	0.2582	0.2598	0.2613	0.2634	0.2658	0.2684	0.2716	0.2747	0.2782	0.2811	0.2831	0.2856
0.960	0.2549	0.2566	0.2578	0.2593	0.2612	0.2633	0.2655	0.2685	0.2710	0.2746	0.2767	0.2799	0.2811	0.2825
1.000	0.2547	0.2564	0.2576	0.2591	0.2610	0.2630	0.2653	0.2679	0.2709	0.2738	0.2768	0.2786	0.2794	0.2794
1.040	0.2544	0.2565	0.2576	0.2593	0.2608	0.2627	0.2653	0.2678	0.2708	0.2727	0.2747	0.2769	0.2769	0.2765
							v							
0.440	1.7813	1.7820	1.7820	1.7833	1.7863	1.7893	1.7923	1.7967	1.7966	1.7977	1.7973	1.7932	1.7901	1.7850
0.480	1.7748	1.7763	1.7787	1.7800	1.7843	1.7881	1.7907	1.7934	1.7952	1.7929	1.7923	1.7901	1.7866	1.7811
0.520	1.7694	1.7734	1.7758	1.7769	1.7808	1.7845	1.7884	1.7907	1.7911	1.7920	1.7897	1.7860	1.7823	1.7784
0.560	1.7644	1.7701	1.7732	1.7748	1.7794	1.7822	1.7856	1.7877	1.7885	1.7864	1.7857	1.7820	1.7779	1.7725
0.600	1.7620	1.7668	1.7692	1.7727	1.7770	1.7792	1.7826	1.7835	1.7833	1.7831	1.7805	1.7782	1.7733	1.7689
0.640	1.7580	1.7631	1.7671	1.7707	1.7732	1.7757	1.7788	1.7794	1.7795	1.7779	1.7753	1.7716	1.7686	1.7652
0.680	1.7550	1.7602	1.7640	1.7676	1.7707	1.7711	1.7757	1.7759	1.7754	1.7741	1.7700	1.7666	1.7630	1.7612
0.720	1.7536	1.7580	1.7616	1.7647	1.7661	1.7698	1.7708	1.7722	1.7693	1.7683	1.7652	1.7617	1.7574	1.7562
0.760	1.7497	1.7553	1.7568	1.7600	1.7635	1.7656	1.7649	1.7652	1.7662	1.7624	1.7593	1.7554	1.7548	1.7528
0.800	1.7474	1.7506	1.7538	1.7557	1.7581	1.7611	1.7613	1.7603	1.7596	1.7561	1.7525	1.7512	1.7509	1.7494
0.840	1.7430	1.7487	1.7500	1.7522	1.7545	1.7547	1.7551	1.7548	1.7535	1.7499	1.7469	1.7473	1.7448	1.7497
0.880	1.7392	1.7438	1.7446	1.7487	1.7490	1.7492	1.7478	1.7487	1.7463	1.7452	1.7403	1.7434	1.7414	1.7493
0.920	1.7357	1.7390	1.7413	1.7423	1.7440	1.7446	1.7443	1.7432	1.7411	1.7389	1.7360	1.7363	1.7417	1.7448
0.960	1.7299	1.7337	1.7358	1.7370	1.7372	1.7373	1.7372	1.7346	1.7344	1.7309	1.7343	1.7331	1.7414	1.7483
1.000	1.7243	1.7279	1.7300	1.7308	1.7310	1.7307	1.7306	1.7297	1.7273	1.7270	1.7258	1.7302	1.7394	1.7525
1.040	1.7196	1.7213	1.7231	1.7232	1.7246	1.7256	1.7237	1.7231	1.7204	1.7238	1.7272	1.7293	1.7423	1.7569

Figure 41. Constant of μ and v